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ABSTRACT

Basic concepts of nuclear structures, radiation, nuclear reactions, and health physics are presented in this text, prepared for naval officers. Applications to the area of nuclear power are described in connection with pressurized water reactors, experimental boiling water reactors, homogeneous reactor experiments, and experimental breeder reactors. Naval nuclear power plants and the propulsion of naval vessels are discussed by using the atomic powered Nautilus (SSN 571) and USS Seawolf (SSN 575). To give enough background for students, related aspects are also explained in the fields of basic and modern physics. The information contained in the appendices includes symbols used in the nuclear area, values of physical constants, unit conversion formulas, a table of atomic masses, uses of general electric charts of the nuclides, a list of the elements, and a glossary of nuclear terms. Illustrations for explanation purposes are also provided. (CC)

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BASIC NUCLEAR PHYSICS

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PREFACE

Basic Nuclear Physics has been prepared to give naval officers a fundamental background in the area of science that applies to new ordnance going into ships--nuclear weapons--and to the newer propulsion systems operated on nuclear power. As the title implies, it is a "basic" text, and as such simplifies much of the complex material of this highly technical area.

With the exception of chapter 9, the text is a reproduction of a book titled Principles of Nuclear Physics, prepared and published by the Special Weapons Training Group, Field Command, Armed Forces Special Weapons Project, at Sandia Base; chapter 9 was prepared by the U.S. Navy Training Publications Center, Washington, D.C. The composite book has been published by the Bureau of Naval Personnel.

FOREWORD

This publication, Principles of Nuclear Physics, has been issued as a source of background information for students attending the nuclear courses of the Special Weapons Training Group, AFSWP. Students whose training in physics is incomplete, or who lack an understanding of the unclassified aspects of nuclear phenomena as revealed by modern research, will find the information in this publication of value in comprehending course material.

Because this publication deliberately has been slanted toward a specific objective, it makes no claim of being exhaustive or all-inclusive. Instructors will be glad to recommend standard texts available from the Special Weapons Training Group, when further information is required.

Users of this publication are invited to report any errors, discrepancies, or omissions they might find. Suggestions for the improvement of future editions will be welcomed.

S. K. Yarbrough

S. K. YARBROUGH
Colonel, Artillery
Officer in Charge

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CHAPTER 1

MATHEMATICAL PRELIMINARIES

SECTION I. ALGEBRA

1. GENERAL

In order to study physics, a student needs to recognize that nature has regular laws by which all its various phenomena operate. Many of these laws are familiar; gravity, centrifugal force, action and reaction, and others. The easiest way of describing the regularity of natural phenomena is by means of the language of mathematics. This chapter will review some of the basic concepts of algebra to give enough background for the studies of nuclear physics which follow.

2. THE USE OF SYMBOLS

a. One of the most important basic ideas of algebra is the use of symbols to represent numbers and numerical quantities. Often problems are greatly simplified by using a letter, such as x or y, to represent a number which is not known or which may not be specified. For example, it is known that there is a definite ratio between the length of the circumference and the length of a diameter of a circle. The ratio is approximately equal to 3.1416, and is abbreviated by the Greek letter pi, which is the symbol π. If a circle has a diameter of 4 cm, it has a circumference of 4π cm. The most general way of writing the natural relation between the lengths of diameter and circumference is by means of symbols, rather than by numbers which apply only to a specific case. Thus if the symbol d represents diameter, then the symbols πd provide a convenient way of writing π times d, or circumference. If the symbol = is used to mean equals, or is equal numerically to, then it is possible to write:

$$\text{Circumference} = \pi d$$
$$\text{or } C = \pi d.$$

In algebra, the multiplication sign (x or $\cdot$) is often omitted, and multiplication is indicated by placing the two symbolic quantities side by side.

b. The value of use of symbols is seen when two things are considered:

(1) $C = \pi d$ expresses a very general rule of nature, not only a fact true for certain numerical instances. When it is desired to use this rule, substitute numbers for symbols and solve the equation.

(2) When complicated formulas are needed to describe natural processes, symbols are usually easier to manipulate than the numbers they represent.

3. EQUATIONS

a. The quantitative rules of nature are normally best expressed by saying that a certain symbolic representation equals another one. This already has been shown in the relation $C = \pi d$, which expresses an equality of two quantities. Such relations are called equations, or formulas.

b. When general rules are expressed as equations, particular cases are usually called solutions. For example, knowing that $C = \pi d$, the question might be asked, "What is the circumference of a circle whose diameter is 6 inches?" The solution to this problem is:

$$C = 6\pi \text{ inches.}$$

Or the question might be asked, "What is the diameter of a circle whose circumference is 100 inches?" The solution to this problem is:

$$d = \frac{C}{\pi} = \frac{100}{\pi} \text{ inches.}$$

c. In solving the second problem, use was made of a fundamental law of algebra, one which will be used constantly, that whenever any operation is performed on one side of an equation, the equality is preserved only if the same operation is performed on the other side. This means simply that both sides of the equation $C = \pi d$ may be divided by the quantity π, and the equation will still be valid.

$$\frac{C}{\pi} = \frac{\pi d}{\pi} = d.$$

This law means that any mathematical operation--multiplication, addition, taking a root--may be performed on an equation and the equality retained, providing exactly the same operation is performed on each side of the equation.

d. As an example of the law, assume that one knows the circumferences of a number of circles and wants to find their areas. Also, it is known that:

Area = πr^2, where r is the radius.

If one were to start out with the values of circumference, solve for radius, then find area, much unnecessary arithmetic would be required. This problem may be simplified by keeping the letter symbols:

$$C = \pi d$$

$$\text{and } d = 2r$$

$$\text{Therefore } C = 2\pi r \qquad \text{(substitute 2r for d)}$$

$$\text{or } r = \frac{C}{2\pi} \qquad \text{(divide by } 2\pi\text{)}$$

$$\text{Now } A = \pi r^2$$

$$\text{So that } A = \pi\left(\frac{C}{2\pi}\right)^2 = \frac{C^2}{4\pi} \qquad \text{(substitute } \frac{C}{2\pi} \text{ for r).}$$

The operations described result in a formula, or equation, expressing area in terms of circumference. The problem then can be solved directly without bothering to find radius r. In other words, r was eliminated in the algebraic shuffle. The student should examine each step in the problem above to assure himself that whenever any equation was modified, the same operation of division or multiplication was performed on both sides of the equation, thus maintaining equality. The student should also notice the way in which quantities are substituted in equations; as 2r being substituted for d, and $(C/2\pi)$ being substituted for r.

e. In the course of study here, many equations will be presented, all of which are subject to this same treatment for solution of problems. Try these for practice:

(1) $E = \frac{3}{2} kT$

Solve for T in terms of E and k.

(2) $E = \frac{1}{2} mv^2$

Solve for v in terms of E and m.

(3) Combine (1) and (2). $\left(\text{Let } E_{(1)} = E_{(2)}\right)$.

(4) Find x in the equation: $7x + 5 = 26$.

(5) Find x in the equation: $ax + b = c$.

4. NEGATIVE NUMBERS

a. Find x in the equation: $7x + 8 = 1$.

NOTE

To solve this equation, another concept must be added; that of negative numbers, or numbers less than zero. The idea is not difficult. Imagine a ruler with one end marked "O."

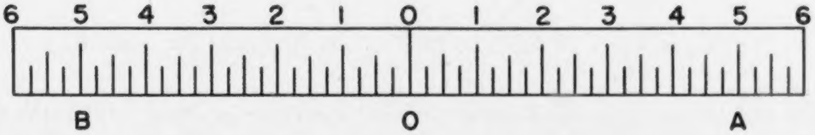

Figure 1. Negative Number Ruler

Point A may be measured at plus 5 inches to the right of O, but for point B, 5 units to the left, it is necessary to place another ruler going in the negative direction. Thus it might be said that B is at -5 units, meaning 5 units on the other side of zero from that side designated positive. In mathematical language, a negative number -a is defined by the equation:

$$(-a) + (a) = 0.$$

b. Simple rules govern their use, specifically, that multiplication or division of a positive number by a negative number gives a negative number. Multiplication or division of two negative numbers gives a positive number. A positive number subtracted from a smaller positive number gives a negative number. Examples of these rules are:

$$(x)(-y) = -xy$$

$$(-x)(-y) = xy$$

$$3 - 6 = -3$$

To solve the problem in paragraph 4a, $7x + 8 = 1$; subtract 8 from both sides, resulting in $7x = -7$; $x = -1$.

5. EXPONENTS AND LOGARITHMS

a. Whenever a number is multiplied by itself, as $a \cdot a$, a convenient notation has been devised to save writing. $a \cdot a$ is written a^2, read "a squared." Similarly, $a \cdot a \cdot a$ is written a^3, and read "a cubed," or "a to the third power." When a number such as a is multiplied by itself n times, the product may be written a^n and is read as "a to the nth power." In this case, n is called the exponent; and a, the base of the exponent.

b. This notation has several convenient advantages. For example, the multiplication of $a \cdot a$ by $a \cdot a \cdot a$ gives the product $a \cdot a \cdot a \cdot a \cdot a$. This problem is more easily written:

$$a^2 \cdot a^3 = a^5.$$

Note that to multiply numbers expressed as powers of the same base, merely add exponents. By the same rule:

$$a^5 \cdot a^3 = a^8, \quad a^{17} \cdot a^3 = a^{20}, \text{ etc.}$$

To multiply a^6 by 1, $a^6 \cdot 1 = a^6$, identically. Therefore $1 = a^0$. Thus $a^0 \cdot a^6 = a^6$, and the rule of adding exponents is valid.

c. Now there must be some number x for which $a^3x = 1$. Following the rules of manipulation,

$$x = \frac{1}{a^3}.$$

Following the rule of adding exponents to multiply, the logical way to write:

$$x = \frac{1}{a^3} \text{ is } x = a^{-3}.$$

Then $a^{-3} \cdot a^3 = a^0 = 1$. Thus division is indicated by a negative power.

It is important to realize that the rule is valid only if the powers are to the same base.

d. Work out to the simplest form:

(1) $(a^3b^2)(a^2b^3)$.

(2) $\frac{(a^3b^2)}{(a^2b^3)}$.

(3) $\frac{(1-x)^3}{(1-x)(1-x^2)}$.

e. In some cases where numbers are to be multiplied together, it is convenient to reduce them all to powers of the same base and add the exponents. The common base for this purpose is the number 10. For example:

$$100 = 10^2$$

$$1,000 = 10^3$$

$$10,000 = 10^4$$

$$1,000,000 = 10^6$$

To multiply 100 x 10,000, one can use the table above, and find that the product is:

$$10^2 \cdot 10^4 = 10^{2+4} = 10^6 = 1,000,000.$$

f. Since 10^0 equals 1 and 10^1 equals 10, it can be deduced that any number between 1 and 10 may be represented as 10 to some power between 0 and 1. In the same way any number between 10 and 100 may be represented as 10 to some power between 1 and 2. In fact any positive number may be represented as 10 to some power. This concept has a very useful application in mathematics.

g. Tables have been made up for all numbers giving the exponent to which 10 must be raised to give each number. The exponents are called logarithms. For instance 2 equals $10^{0.3010}$. Therefore, 0.3010 is the logarithm of 2. Ten is called the base.

h. Any number can be used as the base of a system of logarithms. In mathematics the numbers 10 and e (e = 2.71828) are normally used as bases. A logarithm whose base is 10 is called common logarithm (abbreviated log), one whose base is e is called a natural logarithm (abbreviated ln).

i. From the definition of a logarithm as an exponent, and from the basic laws of exponents, corresponding laws of logarithms may be devised. Use of these laws can save much time in tedious mathematical operations.

j. Law I. The logarithm of the product of two numbers is the sum of the logarithms of the factors. For example:

$$\begin{array}{r} \log 2 = 0.3010 \\ \log 3 = \underline{0.4771} \\ \log 6 = 0.7781 \end{array}$$

Referring to a log table, it is found that the number whose log is 0.7781 is six. What has been done is this:

$$\begin{array}{ccccc} 10^{.3010} & \times & 10^{.4771} & = & 10^{.7781} \\ \shortparallel & & \shortparallel & & \shortparallel \\ 2 & & 3 & & 6 \end{array}$$

k. Law II. The logarithm of a quotient is the logarithm of the dividend minus the logarithm of the divisor. For example,

$$\begin{array}{r} \log 6 = 0.7781 \\ \log 3 = \underline{0.4771} \\ \text{(subtracting)} \quad 0.3010 \end{array}$$

Referring to a log table, it is found that the number whose log is 0.3010 is two.

l. Law III. The logarithm of the rth root of a number is the logarithm of the number divided by r. For example,

$$\log 4 = 0.6020$$

dividing by two gives . . . . 0.3010.

Referring to a log table, it is found that the number whose log is 0.3010 is two.

m. The actual log of a number consists of two parts: an integer called the characteristic, and a decimal part called the mantissa. The mantissa is the part which is found in the log table. The characteristic is found by applying the rules:

(1) If a number N is greater than or equal to one, the characteristics of its log is positive and is numerically one less than the number of digits of N to the left of the decimal point.

(2) If a number N is less than one, the characteristic of its log is negative and numerically one greater than the number of zeros between the decimal point and the first nonzero figure. For example,

N	Characteristic
1214	3
62	1
8	0
0.01	-2
0.0036	-3

n. The mantissa is found in a table of logarithms. The mantissa of the common log of a positive number is independent of the position of the decimal point. The value of the mantissa depends only on the arrangement of the digits in the number. This can be seen from this table:

$$5670 = 5.67 \times 10^{3} = 10^{.7536} \times 10^{3} = 10^{3.7536} \text{ therefore } \log 5670 = 3.7536$$

$$567 = 5.67 \times 10^{2} = 10^{.7536} \times 10^{2} = 10^{2.7536} \text{ therefore } \log 567 = 2.7536$$

$$56.7 = 5.67 \times 10^{1} = 10^{.7536} \times 10^{1} = 10^{1.7536} \text{ therefore } \log 56.7 = 1.7536$$

$$5.67 = 5.67 \times 10^{0} = 10^{.7536} \times 10^{0} = 10^{0.7536} \text{ therefore } \log 5.67 = 0.7536$$

o. When the number is positive but less than one, it might be expected that the log would be written as a negative number. For example,

$$0.567 = 5.67 \times 10^{-1} = 10^{.7536} \times 10^{-1} = 10^{-0.2464} \text{ or } \log 0.567 = -0.2464$$

p. However in practice, such logs are normally written as a negative characteristic plus a positive mantissa, as $\log 0.567 = \bar{1}.7536$, or more commonly $9.7536 - 10$. It can be seen that $9.7536 - 10$ is the same as minus 0.2464. The form $9.7536 - 10$ is more easily manipulated in problems.

SECTION II. THE SLIDE RULE

6. GENERAL

a. The slide rule is an instrument used to made rapid calculations. It is invaluable to the scientist and the engineer. However, it should be remembered that in slide rule work, accuracy is to some extent sacrificed for speed and that slide rule answers are in most cases only close approximations. These approximations are normally good enough for any but the most exact work.

b. The central sliding part of the rule is called the slide, and the other part the body. The glass runner is called the indicator, and the line on the indicator is the hairline. The marks at the ends of the C and D scales labeled 1 are called indices.

7. MULTIPLICATION

Multiplication is performed using the C and D scales.

a. Place either index of the C scale over one of the numbers to be multiplied on the D scale.

b. Place the hairline over the other number on the C scale. Should the number on the C scale not be opposite any number on the D scale, perform step a again, but this time place the other index of the C scale opposite the first number to be multiplied on the D scale. Then proceed to step b.

c. Read the answer under the hairline on the D scale.

d. Since no decimals appear on the scales (2.46, 246, 0.246, etc., are indicated by the same point on the scales), the position of the decimal point must be determined. A rough mental calculation will normally suffice for this.

8. DIVISION

Division is also performed on the C and D scales.

a. Place the hairline over the dividend on the D scale.

b. Set the divisor on the C scale under the hairline.

c. Read the answer on the D scale under the index of the C scale.

9. POWERS

a. One other slide rule operation must be learned. That is the raising of e to a power. e is the base of natural logarithms and equals 2.71828 . . . . It is useful in many physical processes. For example radioactive decay of certain elements follows the law,

$N = N_o e^{-\lambda t}$

N_o = number of atoms at some time zero.

N = number of atoms left undecayed at some time t.

λ = a constant.

b. A log log slide rule may be used to raise e to positive and negative powers. To raise e to a positive power:

(1) Line up the C and D scales so that their indices match.

(2) Place the hairline over the exponent on the C and D scales.

(3) Read the answer under the hairline on the LL1, LL2, or LL3 scale, depending on the value of the exponent. If the exponent is between 0.01 and 0.1, use the LL1 scale; if between 0.1 and 1, use LL2 scale; if between 1 and 10, use the LL3 scale.

c. To raise e to a negative power,

(1) Line up the C and D scales so that their indices match.

(2) Place the hairline over the exponent on the C and D scales.

(3) Read the answer under the hairline on the LL01, LL02, or LL03 scale, depending on the value of the exponent. If the exponent is between 0.01 and 0.1, use the LL01 scale; if between 0.1 and 1, use the LL02 scale; if between 1 and 10, use the LL03 scale.

10. SLIDE RULE PRACTICE PROBLEMS

a. 27×45

b. 313×22.2

c. 0.0426×0.379

d. 123×0.127

e. 1.022×162

f. $325 \times 44 \times 0.121$

g. $\frac{327}{6.21}$

h. $\frac{6.32}{1.045}$

i. $\frac{0.032}{4.30}$

j. $\frac{(9.66) \times (6.81)}{1.24}$

k. $e^{+4.1}$

l. $e^{-4.1}$

m. $e^{-0.12}$

n. $e^{-.311}$

o. $e^{-8.88}$

p. $e^{-.012x} = 0.15$. Solve for x.

CHAPTER 2

BASIC PHYSICS PRELIMINARIES

SECTION I. GENERAL

11. INTRODUCTION

This chapter is intended as a basic physics prerequisite for the course. The whole field of physics is not represented. Only those subjects are included which are required for a basic understanding of later work. These sections should be read with care by those students who have had little or no previous experience with the subjects contained herein.

SECTION II. FORCE, MASS, ACCELERATION

12. FORCE

A force is a physical entity which will tend to move a mass. In other words, a force is a push or a pull exerted on some object. This force or push must be described in terms of both magnitude and direction.

13. MASS

In the above description, the word mass was used, and it should be defined in terms of a force. Mass is that property of a body which resists a change in motion of that body. This means simply that a body which has mass will resist being moved by a force.

14. ACCELERATION

a. To make the interplay of forces and masses clear, the student needs to know what is meant by a change in motion. Whenever the velocity of a body is changed, it is said to accelerate. (Deceleration is a special case in which the speed decreases.) If the speed changes, the average acceleration is determined from the formula,

$$\text{average acceleration} = a = \frac{V_2 - V_1}{t}$$

where V_2 is the final speed, V_1 is the initial speed, and t is the time during which the body accelerates.

b. Now with the concept of acceleration as the rate of change of velocity, a simple single equation can be written which shows how force and mass are related:

$$F = ma.$$

In other words, the force required to accelerate a body is proportional to the mass of the body and to the acceleration produced. Another way of saying this is that the acceleration produced by a force is proportional to the force and inversely proportional to the mass of the body:

$$a = F/m.$$

c. If the velocity is being measured in cm/sec, then the most convenient unit of acceleration is cm/sec per sec. The common scientific unit of mass is the gram. With acceleration measured in centimeters per second per second (cm/sec/sec), then the dimensions of force are:

$$\frac{\text{gm cm}}{\text{sec/sec}} = \frac{\text{gm cm}}{\text{sec}^2}$$

a unit which is called a dyne. Thus a dyne is a unit of force in the metric system cgs units.

15. STANDARDS OF MASS

The gram unit of mass is defined as the mass of a cubic centimeter of water at 4° C. From this standard of mass have been made the primary standards of various masses, such as 1 gram and 1 kilogram, which are kept in carefully controlled conditions at the National Bureau of Standards in Washington, D. C., and at other places. To measure a mass, a standard known mass is placed on one side of a balance, and the unknown mass on the other side for comparison.

16. WEIGHT

a. If a mass is allowed to fall freely in the gravitational force of the earth, it accelerates at approximately 980 cm/sec^2. From the

22

formula, F = ma, it is seen that the earth's gravity exerts a 980-dyne force on a 1-gram mass. This force is called the weight of the mass in the earth's field. On the moon, the weight of a 1-gram mass is about one-sixth of its earth weight because of the moon's weaker gravitational field. This illustrates the difference between mass and weight. Mass is the inertial property of matter; weight is the force the mass experiences in a gravitational field.

b. Weight is measured by measuring the force exerted by the earth upon an object. This force is the same as the force needed to support the object at rest. Springs may be calibrated in terms of force or weight and used to weigh things. In figure 2, the object weighs four units. It should be noted that this weight measurement is different in principle from the mass measurement of figure 3. In the comparison method, a mass will measure the same on the moon, or any place else, while the calibrated spring weighing method gives a different weight at points with different gravitational accelerations. Often the gram unit is used to indicate a force of 980 dynes. This is not strictly correct, but it is useful. Thus a 1-gram mass, at sea level, is sometimes said to have a "weight" of 1 gram. The student should remember that measuring weight in grams is simply a convention and that it is mass which is correctly measured in grams.

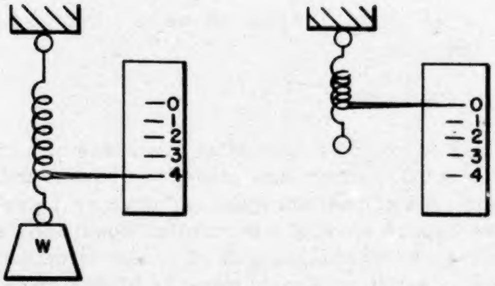

Figure 2. Spring Balance

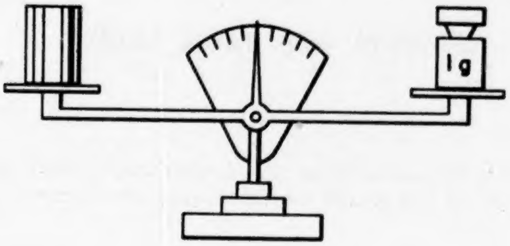

Figure 3. Balance

17. MOMENTUM

When an object having mass moves, it is said to possess momentum. Momentum is the quantity of motion of a body and is given by the formula:

$$P = mv.$$

The greater the momentum of a body, the greater the force needed to bring it to rest in a given time.

18. PROBLEMS

a. How much force is exerted by the earth's gravitational field on a 50-gram mass?

b. If a force of 300,000 dynes is applied to an object whose mass is 210 grams, what acceleration will result?

c. An object of 60-gram mass increases in velocity from 100 cm/sec to 220 cm/sec in 4 seconds. What average acceleration is produced? What average force is exerted to effect this acceleration?

d. If an object in the gravity field feels 1,960,000 dynes of force, what is its weight in grams?

SECTION III. WORK, POWER, ENERGY

19. WORK

a. Work is a physical entity of extreme importance in all scientific thinking. *Work* is defined as the motion of a force through a distance.

$$\text{Work} = W = F \cdot s$$

The work done on a body is the force exerted on it times the distance through which this force was exerted. Whenever a force is exerted over a distance, work is done.

b. A common metric unit of work is the *erg*. An erg of work is done if a force of 1 dyne moves through a distance of 1 centimeter. An erg is thus a very small amount of work, by everyday standards. (For everyday physics, 10^7 ergs is called a *joule*.) However, for atomic physics, an erg is an extremely large unit, and smaller units of work are often used. These will be discussed in section II of chapter 3.

20. POWER

a. The rate at which work is done is called *power*. A given amount of work may be done slowly or rapidly. If done slowly, the power involved is smaller than if it is done rapidly.

$$\text{Power} = \frac{\text{work}}{\text{time}}$$

An everyday unit of power is the watt, which is the power if 1 joule of work is done each second.

$$1 \text{ watt} = \frac{1 \text{ joule}}{\text{sec}} = \frac{10^7 \text{ erg}}{\text{sec}}$$

b. It now should be noted what ergs and watts are in terms of masses, forces, and distances. If an erg of work is done by 1 dyne in 1 centimeter, then:

$$\text{ergs} = \text{dyne} \times \text{cm}$$

$$= \frac{\text{gm cm}}{\text{sec}^2} \times \text{cm} = \frac{\text{gm cm}^2}{\text{sec}^2}$$

These units, expressed in terms of masses, length, and time, are often useful in the solution of problems. See section II of chapter 3.

21. ENERGY

a. When work is done on a body by exerting a force and by moving it, then the work is not lost, but is converted to kinetic energy. Energy is the ability of a body to do work, so the moving body may do work on another body. Kinetic energy is energy of motion. Whenever any mass moves, it possesses kinetic energy in the amount:

$$\text{K.E.} = 1/2mv^2,$$

where v is the velocity of the mass m.

b. When work is done on a body against a force, such as gravity, which places the body in a position in which the force may act when the body is released, the body possesses potential energy, or energy of position. A common example is the lifting of an object to some height h. If the mass of the body is m, the force exerted in lifting it is mg, and the work done is:

$$W = mgh,$$

where g is the acceleration due to gravity (980 cm/sec^2). The potential energy of the body in position h units above the floor is then,

$$\text{P.E.} = mgh.$$

If the body were dropped, it would be able to do this much work when it struck the floor. The potential energy first would be converted to kinetic energy as the object drops, then this kinetic energy would do work in breaking the object, or heating the floor slightly.

c. The preceding discussion illustrates a fundamental rule about energy--energy may be converted from one form to another, but it is never destroyed or created--the law of conservation of energy. It will be seen later how this classical statement needs reinterpretation for modern atomic physics.

d. Potential energy may be converted to kinetic energy, as in the falling body. As the object drops, the P. E. = mgh at each instant decreases, since h, the height from the floor decreases. The body is accelerated with force mg; it acquires velocity as it drops; and thus acquires kinetic energy:

$$\frac{mv^2}{2}.$$

The final velocity upon impact is determined by equating the original energy (all of which was potential), mgh, to the final energy,

$$\frac{1}{2}mv^2$$

all of which is kinetic.

$$mgh = \frac{1}{2}mv^2$$

$$v = \sqrt{2gh}$$

The student should verify that the algebra involved in solving for v is correct and that the units work out correctly. Remember g is the acceleration due to gravity.

e. Conversely, kinetic energy may be changed into potential energy, as in the case of a rifle bullet fired into the air. It leaves the gun with a velocity, v, and essentially zero potential energy. It loses velocity, decelerating due to the force of gravity with an acceleration of -g until it reaches a height h where it stops, and all its energy is potential. Then it falls again to earth, until it has lost all potential energy at impact. The height to which the bullet climbs is derived by setting its kinetic energy equal to the maximum potential energy achieved.

$$\frac{1}{2}mv^2 = mgh$$

$$h = \frac{v^2}{2g}$$

Again the student should verify this.

f. Energy may exist in other forms than kinetic and potential. Some of these other forms will be described in this course. Heat energy, it will be shown, is a special kind of kinetic energy; mass energy and nuclear energies are special kinds of potential energies.

22. PROBLEMS

a. How much work is done on a body by a force of 1,000,000 dynes acting through 1 meter? How much kinetic energy does the body possess after this process?

b. How much power is required to do 10^{16} ergs of work in 2×10^{-5} seconds?

SECTION IV. HEAT ENERGY

23. HEAT AND TEMPERATURE

a. Care should be taken to differentiate between heat and temperature. Heat is a measure of energy. As heat is added to a body, some of the energy added manifests itself as kinetic energy of the molecules in the body. Not all the molecules in the system will have the same kinetic energy, but the average kinetic energy per molecule may be considered to be the temperature of the body. Temperature is normally measured by comparison with a body at a known temperature.

b. Suitable bodies at known temperatures are freezing and boiling water. In the commonly used Centigrade scale, freezing water is arbitrarily designated as being at 0° C. and boiling water as being at 100° C. In the Fahrenheit scale, 32° F. corresponds to 0° C. and 212° F. corresponds to 100° C. To convert from one system to the other, the following formula is used:

$$\text{Temperature in } {}^{\circ}\text{F.} = \frac{9}{5}\,(\text{temperature } {}^{\circ}\text{C.}) + 32^{\circ}.$$

c. If one can imagine a system in which heat has been removed until the molecules have no kinetic energy, one would have a body at the lowest possible temperature or Absolute Zero. This situation should take place at -273.18° C. Although this temperature has never been reached, it has been selected as zero for another scale called the Kelvin (° K.) scale. Since the Kelvin scale uses degrees as basically defined by the Centigrade scale, 0° C. corresponds to 273.18° K. and 100° C. corresponds to 373.18° K. For convenience in those applications where absolute accuracy is not required, absolute zero is generally taken as -273° K.

d. In most scientific work, heat is measured in terms of calories, from which it can be converted into other energy terms (e.g., joules, foot-pounds) if the need arises. A calorie is defined as the heat energy required to raise 1 gram of water 1 degree centigrade.

24. SPECIFIC HEAT

As heat energy is added to a body, the temperature increase is measured, and a quantity called specific heat is calculated. Specific heat is the ratio of heat added to temperature rise occasioned by this energy. Specific heats vary between different substances. The units of heat are chosen so that water has a specific heat of 1 calorie/g °C. In other words, a calorie is the heat energy required to raise 1 gram of water 1 degree centigrade. From other experiments involving the generation of heat by mechanical means, it is known that one joule (10^7 ergs) of energy is equivalent to 0.24 calories. This equivalence of mechanical work and heat energy was a decisive refutation of the old heat-fluid theory.

25. THERMAL EXPANSION

Many substances change their physical dimensions when their temperature is changed. Most metals expand slightly with increase in temperature and contract with decrease. The same is true for fluids, except the expansion is relatively greater; this effect is used in many thermometers to measure temperature.

SECTION V. KINETIC THEORY

26. MOLECULAR MOTION

a. The various heat phenomena are all explainable from one basic assumption. This assumption has had undeniable experimental verification since about 1900. All matter is composed of small building blocks, which are particles called molecules. These molecules are much too small to be seen even with the most powerful optical microscopes, but the effects of their behavior may be measured. Molecules are in continuous random motion, bouncing around and colliding with each other. The basic assumption is that this random motion of molecules is responsible for the thermal behavior of gases. The internal structure of the molecules is also partly responsible for the behavior of matter at extremely high or low temperatures.

b. As early as the 1820's, a botanist named Brown had noticed with a microscope that pollen grains suspended in water were in constant agitation with apparently random motions. This phenomemon became known as Brownian movement. In 1908, the French scientist, Perrin, prepared particles smaller than pollen grains, and of definitely known sizes and masses, and suspended them in various liquids. He found that the Brownian movement really was random, and that the vigor of this motion depended strikingly upon the temperature of the liquid, the type of liquid used to suspend the colloidal particles, and the mass of the particles. The results fit perfectly with the theory that these visible particles are being bombarded and moved continuously by invisible molecules of the liquid. Thus, a fairly direct proof of the existence of molecule is available by which measurement may be made of their masses and other properties. More modern experiments confirm these results in other ways.

27. DEFINITIONS

a. A molecule is the smallest particle of a substance which retains the normal chemical properties of that substance. Molecules are composed of one or more particles called atoms. An atom is the smallest particle of an element which retains the chemical properties of that element. An element is a substance which cannot be separated into substances different from itself by ordinary chemical means.

b. To illustrate these definitions, consider a molecule of water, (H_2O). The molecule is composed of 2 hydrogen atoms and 1 oxygen atom, bound together as a unit with the chemical properties of water. The hydrogen atoms or the oxygen atom, if split apart from the molecule, have the chemical properties of the elements hydrogen and oxygen, respectively. Neither hydrogen nor oxygen atoms can be broken down by chemical means to form substances with other chemical properties; hence they are elements. Further examples of elements are copper, iron, tin, nitrogen, and uranium. It is seen that the molecules of many elements, iron for example, are the same as the atoms of that element. For many elemental gases, this is not so. In these gases, two similar atoms pair up to form a molecule.

28. KINETIC THEORY

a. In using the assumption of kinetic theory to explain thermal behavior of gases, the student normally will be unconcerned with the detailed internal structure of the molecules. He will only need to remember that these molecules are moving about in a completely random way. The principal result of the theory is the understanding that heat energy is the energy of random motion of the molecules.

b. Although individual instantaneous motion of a molecule is random, the average velocity of a molecule over a period of time, or the average instantaneous velocity of a large number of molecules, is not random. The temperature of a gas depends directly upon the average energy of the molecular motions. If heat energy is added to a gas, the molecules speed up somewhat, their average energy is increased, and the temperature is increased.

c. The average kinetic energy of a single molecule is:

$$\frac{1}{2} m\bar{v}^2,$$

where $\bar{v}$ is the average velocity of the molecule and m is its mass. The total energy of a gas containing N molecules is thus:

$$\frac{N}{2} m\bar{v}^2.$$

The absolute temperature T for a monatomic gas may be obtained from the equation:

$$\frac{3}{2} kT = \frac{1}{2} m\bar{v}^2$$

k is called Boltzmann's constant, where:

$$k = 1.38 \times 10^{-16} \text{ erg/}^\circ \text{ K. / molecule.}$$

It is seen at once that absolute zero is the temperature at which all molecular motion ceases. This equation results from assuming that the molecular energy determines the temperature.

29. PROBLEM

Use $3/2\ kT = 1/2\ m\bar{v}^2$ to calculate the average velocity of a hydrogen molecule H_2 in a gas at 20° C. The mass of a hydrogen atom is 1.6×10^{-24} grams.

30. THE MAXWELLIAN DISTRIBUTION OF VELOCITIES

a. Consider a gas at a certain temperature, for example, oxygen, enclosed in a 1 cubic centimeter box at a temperature T_1. All of the molecules of oxygen will be in motion, and they will be moving in all different directions and at varying rates of speed; that is, they will all have different velocities. In this discussion, the word velocity will be taken to mean the magnitude of the velocity without regard to the direction of motion of the molecules.

b. The velocity of the molecules will vary over a very great range. Some molecules will travel very slowly while a few will travel very fast. For the specific temperature T_1, there will be some velocity v_p which is most probable, known as the most probable velocity.

c. If the temperature is now raised to a new temperature T_2, the average velocity of the molecules is also raised because an increase in temperature is an indication of increased kinetic energy and hence increased velocity. When the temperature is raised, more molecules will travel at the higher velocities and fewer molecules at the lower velocities. It is possible to represent this variation in velocities for a particular temperature by means of a curve such as is shown in figure 4. This curve is known as the Maxwellian distribution of velocities. In this distribution, the total number of oxygen molecules is represented by the area under the curve. The shaded area under the curve represents the number of molecules with energies greater than v_1 but less than some higher velocity v_2.

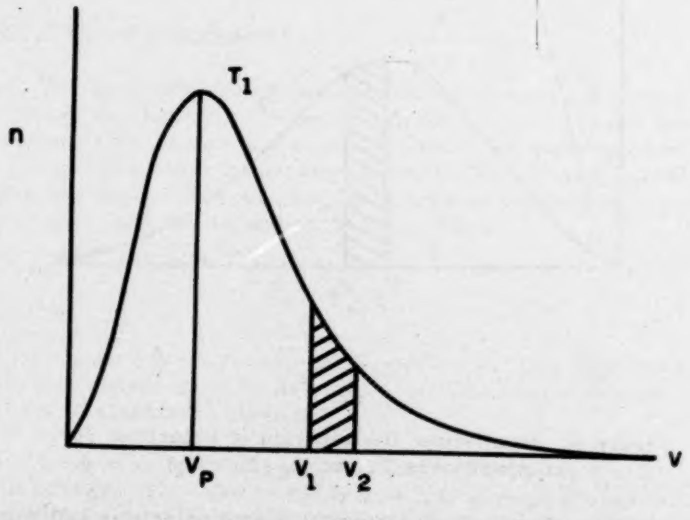

Figure 4. Maxwellian Distribution of Velocities for Temperature T_1

The effect of increasing the temperature to T_2 is shown in figure 5. Here the curve for the lower temperature T_1 has been included for comparison. The total area under both curves will remain the same because the total number of molecules is unchanged. The areas under the curve at higher velocities, such as between v_1 and v_2, have increased indicating that more molecules are traveling at these higher velocities.

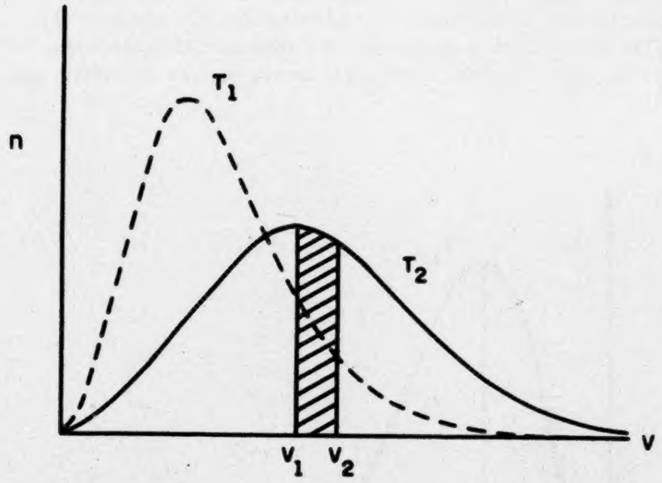

Figure 5. Maxwellian Distribution of Velocities for Temperatures T_1 and T_2 ($T_1 > T_2$)

d. The fact that there is a distribution of velocities and that this distribution changes at higher temperatures is of considerable importance later in this course.

SECTION VI. ELECTRICITY

31. GENERAL

a. This section will not be concerned with electric circuits, but with a few basic principles of electrostatics and the behavior of electric charges.

b. In every atom of any material, there are two types of electricity which are called positive and negative charges. From experiments involving the passage of electricity through gases, it has been learned that the negative electric charge is quite mobile and is essentially responsible for the phenomenon of electric conduction. These negative charges are called electrons.

c. Whenever a body becomes electrically charged, it has either gained an excess of electrons or has lost some of its electrons, leaving the residual net charge negative or positive, respectively. Bodies may be charged with electricity in various ways, a common one being the frictional rubbing off or on of electrons.

32. ACTION AT A DISTANCE

a. The most significant fact about electric charges is that they exert forces on each other, even though the charges are not touching. This action at a distance is a general property of many types of forces in physics, such as gravity, electricity, and magnetism. In the case of electric charges, the force exerted depends on the sizes of the charges and the distance r between them:

$$F \propto \frac{q_1 q_2}{r^2}$$

where q_1, q_2 are the charges, the $\propto$ sign means is proportional to. The units of charge must be defined before this proportion can be made into an algebraic equation.

b. A common scientific unit of charge is the electrostatic unit (esu) of charge. This unit is defined as that amount of charge which will exert a force of 1 dyne on an identical charge placed 1 centimeter away. By careful measurements, it has been found that an electron has a charge of:

$$-4.8 \times 10^{-10} \text{ esu.}$$

The minus sign indicates that an electron is the negative type of electricity.

Now if we measure charges q_1 and q_2 in esu and the distance between them in centimeters, the force F in dynes is:

$$F = \frac{q_1 q_2}{r^2}.$$

This force will be attractive, positive, if the charges are of opposite sign; and repulsive, negative, if the charges are alike.

c. Picking up bits of paper with a charged comb illustrates these electrostatic forces. By combing the hair rapidly, an excess of electrons may be rubbed onto the comb, leaving it with a net residual negative charge. As the comb is placed near the paper bits, the negative charges on the comb exert forces on the electrons in the paper, repelling some of them toward the far side of the paper. See figure 6.

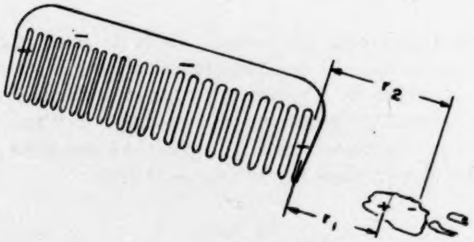

Figure 6. Electrified Comb

The paper then has a slight positive excess on the side next to the comb, and a slight negative excess on the side away from the comb. The distance between the comb and the positive charge is less than that between the comb and the negative. Therefore, the net force exerted on the paper will be an attractive force.

$$\text{Attractive force } F_1 = \frac{q_{comb}\, q_{paper}\,(+)}{r_1^2}.$$

$$\text{Repulsive force } F_2 = \frac{q_{comb}\, q_{paper}\,(-)}{r_2^2}.$$

Net force = $F_1 - F_2$, attractive, since r_2 is slightly larger than r_1.

33. POTENTIAL DIFFERENCE

a. The student should notice now that a charge possesses potential energy when it has a force exerted on it by another charge. In other words, it can do work by virtue of its position. Or, conversely, work must be done to move it against the electric force. For example, consider a positive and a negative charge. They will move toward each other. If one charge is held in a fixed position, a force must be exerted on the other to move it away from the fixed charge and work is done. The potential energy of a charge at some point in the electric field of another is defined as the work that would be done in moving that charge from infinity to its present position. According to Coulomb's law:

$$\text{P.E.} = \frac{q_1\, q_2}{r}$$

where r is the distance between the two charges. This energy of interaction of two charges will be important for our later discussion of atomic structure.

b. It is often convenient to think of the work that can be done by an electric field in terms of potential difference. The unit of potential difference is the volt. It is possible to think of voltage as a sort of electrical pressure which pushes charges around. The electrostatic unit system has a unit of potential difference called the stat volt, or e.s. volt; which is a large unit for practical everyday electrical work. The practical volt is 1/300 esv.

c. An esv is that amount of potential difference through which one erg of work is done in moving an esu of charge. Potential difference is a unit of energy difference per charge unit; it is a specific potential energy change. To illustrate the use of this definition, calculate the energy gained by an electron passing through 1-volt potential difference:

$$\left(\frac{1}{300}\ \text{esv}\right)(4.8 \times 10^{-10}\ \text{esu}) = 1.6 \times 10^{-12}\ \text{ergs.}$$

34. MAGNETIC EFFECTS

Whenever a charge moves through space, an electric current is said to flow, and some kind of a magnetic field is set up. Magnetic fields exert forces on other magnetic fields, such as those generated by other currents or by permanent magnets. It is not necessary to be very concerned here about the details of magnetic forces, except to note that a changing or moving magnetic field will induce or set up an electric field. This complementary fact to the first sentence in this paragraph was discovered in the last part of the 19th century and is important to our understanding of generators and of electromagnetic waves, such as radio and light.

35. PROBLEMS

The following problems summarize the salient points of this section:

a. Calculate the energy in ergs acquired by an electron falling through a potential difference of 1 million volts.

b. What force is exerted between 2 unlike charges of 1 electronic charge each, separated 10^{-8} cm? What is the potential energy of one in the field of the other?

c. What force is exerted between 2 like charges of 1 electronic charge each, separated 10^{-12} cm? What is the potential energy of one in the field of the other?

SECTION VII. ELECTROMAGNETIC RADIATION

36. GENERAL

a. Since this unclassified course material is largely concerned with radiation, a few of the concepts of electromagnetic waves will be introduced here as a preliminary background for later study.

b. All radiation may be considered as a method of transmission of energy. By various means, a molecule, atom, or some part of an atom, may give up some of its energy into a form of radiation. This radiation may travel to some other point of space and then be absorbed by another molecule, atom, or part of an atom. The energy of the radiation is thus added to that of the absorbing matter.

37. MANNER OF PROPAGATION

a. The electromagnetic type of radiation will be discussed. Because of the fact mentioned in paragraph 34 that a varying magnetic field induces an electric field, and the complementary principle that a changing electric field sets up a magnetic field, it is possible to gain a fairly basic understanding of how electromagnetic waves are propagated. Radio waves are an example of electromagnetic waves. A rapidly varying electric current is established in a radio antenna by the transmitter. This current sets up a changing magnetic field in the vicinity of the antenna, which in turn induces a changing electric field. The electric field and the magnetic field then alternately established one another as they move out from the antenna. This process is illustrated in figure 7. Since electric field lines have both magnitude and direction, they are shown as vectors along a certain line of propagation from the antenna. Notice that the electric and magnetic fields alternately are strong and weak, and that they reverse in direction in a regular way. A complete cycle of the wave is shown by figure 7.

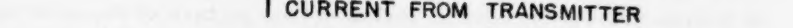

Figure 7. Electromagnetic Waves

b. What is actually happening in the electromagnetic wave is that the electric and magnetic fields propagate, or move along in space, by a mutual interaction. The way in which the fields move is determined by the manner in which one field generates the other. For empty space, an electromagnetic wave moves along with a velocity equal to:

$$2.9976 \times 10^{10} \text{ cm/sec, or } 3 \times 10^{10} \text{ cm/sec,}$$

a value usually abbreviated c, or the speed of light. In other materials, such as glass or water, the velocity of propagation is smaller because of the dielectric properties of these materials. In other words, the way in which the electric field is set up is slightly different in glass than in air or vacuum. This difference in velocity is accounted for in the index of refraction of glass and is the principle of operation of a lens. In this course we are concerned only with the velocity of light in a vacuum. This value seems to be a universal constant of nature.

38. WAVES

a. A wave is any propagated periodic disturbance in a transmission medium. In the case of electromagnetic waves, the disturbance which is propagated is the electric and magnetic field, and they disturb the normal no field condition of empty space in a regular way. Notice from figure 7 that the direction in which propagation occurs is perpendicular to the disturbance being propagated. This fact is true of all transverse waves.

b. A water wave is another example of a transverse wave; the disturbance of the water moves up and down, the wave itself moves horizontally. As an example of a nontransverse wave, consider a long coiled spring, which is given periodic taps at one end. The disturbance in this case is a compression or extension of the spring, parallel to the direction of propagation. This type of wave, of which sound waves are the most common example, is called longitudinal. This course will be mostly concerned with transverse waves, since electromagnetic waves are of this type.

39. WAVE PICTURE

If it were possible to take an instantaneous picture of the electric field vectors in an electromagnetic wave, the picture might look like figure 8. The arrows represent the direction of the field; and the height of the curve, the magnitude. Notice the regular way in which the field varies. If one measured the variation of the field at a single point, he would find that it varied as a function of time, passing through regular peaks and valleys. To see this, imagine yourself at a point P on the axis, and let the wave move by you. The wave is positive, then negative, then positive again, in the same regular way. This periodicity in both space and time characterizes all wave propagation.

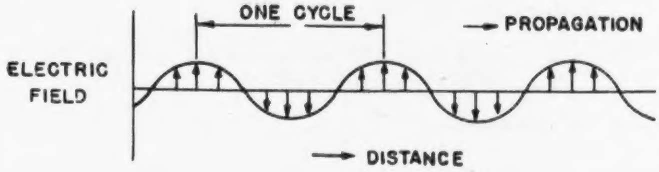

Figure 8. Wave Picture

40. DEFINITIONS

a. A few basic definitions should be learned. The distance between corresponding adjacent points on a wave is called a wavelength, abbreviated by the Greek letter lambda, λ. A cycle is the complete wave between two corresponding points. Thus a wavelength is the distance in which a cycle is accomplished. The number of cycles which pass a given point in a second is called the frequency of the wave, abbreviated ν (nu).

b. For a wave of wavelength λ traveling at a velocity c, it will be seen that the number of cycles which pass a fixed point in a second is c/λ, thus:

$$\nu = \frac{c}{\lambda}.$$

Conversely, if a number ν cycles per second are observed, and each one is λ long, then the speed with which they pass is $\lambda\nu$. Thus $\lambda\nu = c$. The student should attempt this reasoning for deriving this formula in the form:

$$c/\nu = \lambda.$$

This relation between frequency, wavelength, and velocity of propagation is a general formula holding for all types of wave propagation.

c. Example problems:

(1) What is the wavelength of a radio wave whose frequency is 1000 kc/sec?

40

(1 kc = 1000 cycles)

$$\lambda = \frac{c}{\nu} = \frac{3 \times 10^{10} \text{ cm/sec}}{1,000,000 \text{ cycles/sec}} = 3 \times 10^4 \text{ cm}$$

$= 300$ meters.

(2) A velocity of light determination is made from a frequency and wavelength measurement.

$\nu = 6.700 \times 10^8$ cycles/sec.
$\lambda = 44.70$ cm.
What is c? $\nu\lambda = 2.99 \times 10^{10}$ cm/sec.

d. The time for one cycle is called the period of the wave. Thus the period T is the reciprocal frequency,

$$T = \frac{1}{\nu}.$$

For example, the period of a 1-megacycle frequency wave is 1 microsecond.

e. Wave number is a useful term for dealing with light waves. The wave number, abbreviated $\bar{\nu}$, or n, is defined as the reciprocal wavelength,

$$\bar{\nu} = \frac{1}{\lambda},$$

and therefore has units of cm^{-1}.

Another mathematical definition is $\bar{\nu} = \nu/c$, or frequency divided by velocity. The wave number of light whose $\lambda = 4 \times 10^{-5}$ cm is:

$$\bar{\nu} = \frac{1}{\lambda} = \frac{1}{4} \times 10^5 = 25,000 \text{ cm}^{-1}. \text{ (Violet light.)}$$

f. The angstrom unit, Å, is a useful unit for measuring light wavelengths. It is defined as 10^{-8} cm, so that red light, with $\lambda = 8 \times 10^{-5}$ cm, has $\lambda = 8000$ Å.

41. ELECTROMAGNETIC SPECTRUM

a. It has been noted already that radio waves are electromagnetic. They are waves whose wavelengths range from 20,000 meters to a few centimeters. Infrared rays are electromagnetic waves whose wavelengths range from a few millimeters to about 10^{-4} centimeters. Light rays, visible to the human eye, range in wavelength from 8×10^{-5} to 4×10^{-5} cm. Ultraviolet rays are of shorter wavelength, and X-rays are still shorter. A range of wavelength values such as has been described is called a spectrum. The electromagnetic spectrum is summarized in figure 9.

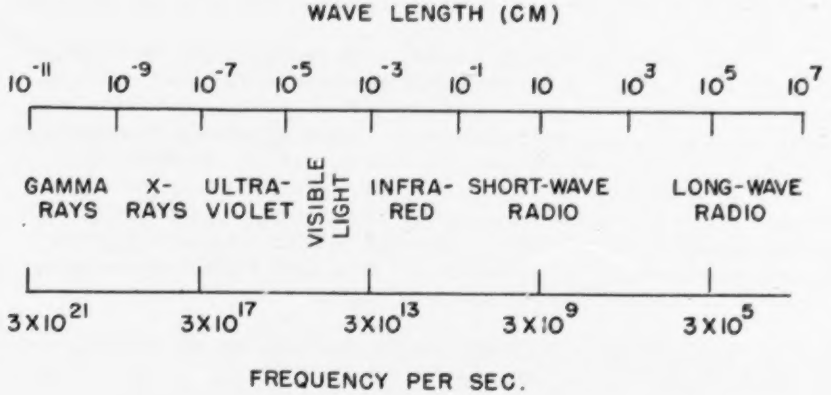
WAVE LENGTH (CM)
10^{-11}
10^{-9}
10^{-7}
10^{-5}
10^{-3}
10^{-1}
10
10^{3}
10^{5}
10^{7}
GAMMA RAYS
X-RAYS
ULTRA-VIOLET
VISIBLE LIGHT
INFRA-RED
SHORT-WAVE RADIO
LONG-WAVE RADIO
3×10^{21}
3×10^{17}
3×10^{13}
3×10^{9}
3×10^{5}
FREQUENCY PER SEC.

Figure 9. Electromagnetic Spectrum

b. These various types of electromagnetic radiation have all the characteristics and properties of electromagnetic waves; frequency, wavelength, velocity = c; and they are all composed of electric and magnetic field variations. However, they may originate in various ways. The longer radio waves are usually generated directly by radio transmitters. The infrared waves are generated by somewhat excited or hot molecules. Heat radiation is infrared. Visible and ultraviolet light are produced by excited atoms by processes to be described later. X-rays are generated in several ways, either by rapid deceleration of charged particles, or by extreme excitation of the atoms in matter. Gamma rays are generally produced in the nuclei of atoms.

42. PARTICLES OR WAVES

a. In experiments with light, ultraviolet and X-rays, physicists have found that there are two types of explanations for the observed phenomena. In many experiments, light rays behave as though they were waves, as described here so far. Interference, diffraction, and polarization experiments are most plausibly explained in terms of electromagnetic waves; that is, light appears to be a long train of waves.

b. In other experiments, however, light rays behave as though they were small particles, bundles of energy, traveling at the velocity c. In a photoelectric effect experiment, and in many experiments with shorter wavelengths, X-rays and gamma rays, the rays appear to be composed of packets of energy called photons. A photon may be absorbed all at once or impart its energy in sudden discrete amounts.

c. The question is often raised as to whether light is composed of photons or waves, since the concepts seem so different. The answer is that light is emitted and absorbed as photons, but travels as though it were a long continuous wave. Light apparently is some kind of phenomenon, not wholly particle-like nor wholly wavelike, but something which may act like either particles or waves in experiments. While this answer may seem intellectually unsatisfying, the student should be comforted to know that it is both unsatisfying and stimulating to experimental and theoretical physicists who are doing research on the fundamental nature of light.

d. The energy of a photon associated with an electromagnetic wave of frequency ν can be shown to be:

$$E = h\nu$$

where h is a known constant number, $h = 6.6 \times 10^{-27}$ erg sec, called Planck's constant. Planck was one of the first physicists to recognize the existence of photons. This concept of photons, and of the energy carried by them, is important principally for the higher frequency, higher energy end of the electromagnetic spectrum.

43. PROBLEMS

a. What is the frequency of a wave whose velocity is 10 meters per second, and whose wavelength is 0.1 meter?

b. What is the wavelength of a station whose frequency is 1500 kc, at the upper end of the broadcast band? What wavelength for a radar frequency of 15,000 Mc?

c. What is the energy of a photon of 15,000 Mc radiant energy? Compare this energy with that of a photon of light energy of 6×10^{-5} cm wavelength.

d. What is the wavelength of a light wave whose frequency is 1.5×10^{15} sec^{-1}? In what part of the spectrum does it lie?

e. What is the frequency of a photon whose energy is 1-electron volt (1.6×10^{-12} ergs)? What wavelength? What part of the spectrum?

f. How much energy is associated with a ray of wavelength 0.01 Å? What frequency? What part of the spectrum?

CHAPTER 3

GENERAL PHYSICS

SECTION I. GENERAL

44. This chapter is composed principally of the actual material presented and required of students in the course. Lecture data and other supplementary information have been added to a bare outline of actual lesson plans. Since this chapter is intended to collate and organize the material into a single unit for study, all the necessary unclassified physics for the course has been included.

SECTION II. ENERGY AND UNITS

45. BASIC

a. In this section are summarized the basic concepts of energy, which ideas already have been expressed in more detail in paragraph 21. They are mentioned here again briefly for the sake of completeness. Also, there is a summary of units useful in this course and in the work for which this course prepares the student.

b. Units are the means of labeling physical quantities. Every physical quantity may be measured and expressed in terms of some units. For example, a distance may be measured as a number of centimeter units. This test will use principally the metric system of units because of its convenience.

c. Three basic dimensions should be noticed: mass (M), length (L), and time (T). It will be found that units for every physical quantity may be expressed in terms of these three dimensions. For example, velocity units are length per time, L/T; acceleration units are velocity per time, or

$$\frac{L/T}{T},$$

which may be written conveniently L/T^2.

46. THE CGS SYSTEM

The system of units used here is the cgs, centimeter-gram-second system, where length is measured in centimeters, mass in grams, and time in seconds. A centimeter is a length based on the distance from the north pole to the equator at a certain longitude. The primary standard meter is kept at the National Bureau of Standards. A gram is defined as the mass of a cubic centimeter of water at 4° C. A primary standard gram mass is also kept at the National Bureau of Standards, from which secondary standards may be calibrated for laboratory use in other places. A second is defined as one 86,400th part of a mean solar day. Recently, this time unit has been redefined in terms of certain colors of light, for easier laboratory calibration. Therefore, it will be seen that the units for measuring physical quantities are well defined and meaningful.

47. FORCE

a. Now the question arises, "What are the units of other physical quantities, as for example, forces and energies?" In order to discuss these units, these physical entities will be defined quantitatively. Remembering Newton's law of motion,

$$F = ma.$$

The cgs unit of mass is the gram; the unit of acceleration is the cm/sec/sec, or cm/sec^2. Therefore, the most convenient unit of force will be gm cm/sec^2, the amount of force which will accelerate a 1-gram mass at 1 centimeter per second per second. This cgs unit of force is called a dyne. One should notice that the dimensions of force are:

$$\frac{ML}{T^2}.$$

b. The force which gravity exerts on a body of mass m, i.e., its weight, is thus equal to mg, where g is the gravitational acceleration. This distinction between weight and mass should be perfectly clear to the student. Weight is the force which acts upon a mass due to the gravitational field; it is the force which causes a mass to accelerate to the earth with an acceleration g. At sea level, $g = 980\ \text{cm/sec}^2$. Mass is the inertial property of matter by which it resists a change in its state of motion, and therefore mass is independent of gravity.

48. WORK

Remembering that work is done when a force is moved through a distance, a convenient cgs unit for work may be found. Since energy is the ability to do work, energy should have the same units.

$$\begin{aligned} \text{Work} &= (\text{force})\,(\text{distance}) \\ &= \text{dyne} \cdot \text{cm} \\ &= \frac{\text{gm cm}}{\text{sec}^2} \cdot \text{cm} = \frac{\text{gm cm}^2}{\text{sec}^2} \\ &= \text{ergs.} \end{aligned}$$

The cgs unit of work or energy is called an erg. It is the work done when 1-dyne force acts through a distance of 1 centimeter. The dimensions of work are ML^2/T^2.

49. POTENTIAL ENERGY

Potential energy, mgh, of a mass, m, at a height, h, above a reference level is also measured in ergs in cgs system, as can be shown by multiplying the units in the above equation.

$$\begin{aligned} mgh &= (\text{grams})\left(\frac{\text{cm}}{\text{sec}^2}\right) \text{cm} \\ &= \text{gcm}^2/\text{sec}^2 \\ &= \text{ergs} \end{aligned}$$

The amount of ergs is the work that can be done when this potential energy is released. In accordance with the law of conservation of energy, potential energy is convertible to kinetic energy, or energy of motion.

50. KINETIC ENERGY

47

Kinetic energy, $\frac{1}{2}mv^2$, also has work units, since

$$gm\left(\frac{cm}{sec}\right)^2 = \frac{gm\ cm^2}{sec^2} = ergs.$$

51. MASS ENERGY

In the early 20th century, Einstein proposed that the law of conservation of energy be modified to include another type of energy, called mass energy. It has been found that mass in some cases may be converted into other forms of energy according to the formula:

$$E = mc^2$$

where m is the mass which converts, and c is the velocity of light, 3×10^{10} cm/sec. The student should verify that E is given in ergs when m is given in grams. The newer law states that the total sum of mass and energy is never destroyed or created, but only converted from one form of energy or mass to another.

52. ELECTROMAGNETIC ENERGY

Since energy is transmitted by radiation, it is necessary to consider the electromagnetic form of energy. Light and other electromagnetic radiations travel like wave phenomena obeying the usual wave equations, such as

$$c = \lambda v$$

where λ is wavelength, v is frequency, and c is the velocity of light. However, light is emitted and absorbed only in discrete quantities, and these packets of light energy are called photons, or light quanta. For an electromagnetic radiation of frequency v, the energy of the photon is

$$E = hv = \frac{hc}{\lambda}$$

h is Planck's constant, 6.6×10^{-27} erg seconds; v is expressed in cycles per second; i.e., sec^{-1}; and E is given in ergs. (The dimensions of the unit cycles per second is 1/T, since a cycle is a dimensionless unit.) This quantum equation means that if an energy, E ergs, is to be released in the form of radiation, it will be emitted as a photon; and when the wavelength of the light is measured, it will be

$$\lambda = \frac{hc}{E}.$$

The most convenient description is given in terms of wave number $\bar{v}$.

$$\bar{v} = \frac{1}{\lambda} = \frac{E}{hc}$$

When light interacts with matter, it acts as if it were composed of particles having definite energy. These particles have momentum, given by

$$p = \frac{E}{c} = \frac{hv}{c} = \frac{h}{\lambda},$$

and apparent mass, given by

$$m = \frac{h}{c\lambda}.$$

Actually the rest mass of a photon must be zero, but in their absorption in matter, they often act as though they had a mass which depends on their wavelength. These quantum considerations are especially true for the higher frequency, higher energy radiations, such as visible light, ultraviolet, X-rays, and gamma rays.

53. MOMENTUM

Another physical entity whose units should be mentioned is momentum, the quantity of motion of a moving body:

$$p = mv$$

where p is momentum, m mass, velocity v. In the cgs system, p has units gm cm/sec. Related to this concept is angular momentum, which is possessed by a body moving around a reference point. If r is the radius from the body to the reference axis (the center of its circular orbit) and p is its linear momentum, then angular momentum L = pr = mvr.

The units of angular momentum are thus:

$$\frac{\text{gm cm}^2}{\text{sec}}$$

in the cgs system, which are the same as the units erg-sec, having dimensions

$$\frac{ML^2}{T}.$$

54. ATOMIC MASS UNITS

When dealing with atoms, the extremely small sizes and masses cause some inconvenience in description by the cgs unit system. The mass of an atom is usually expressed in atomic mass units, or amu. One amu is defined as 1/16 the mass of the oxygen-16 atom. The mass in grams corresponding to one atomic unit is 1.66×10^{-24} grams.

55. ELECTRIC CHARGE

a. The most convenient unit of electric charge in dealing with atomic systems is the electronic charge unit, e. This charge is equal to 4.8×10^{-10} electrostatic units of charge. (One esu is that amount of electric charge which when placed 1 centimeter from an identical charge in a vacuum will experience an electric force of 1 dyne.)

b. The most convenient and most used unit of energy in atomic and nuclear systems is the electron volt, abbreviated ev. One ev is the energy which an electron will pick up in accelerating through an electric field of 1-volt potential difference. Since the electronic charge e is 4.8×10^{-10} esu, and there are 300 practical volts in an electrostatic voltage unit, then the following relation between ergs and ev can be derived:

$$1 \text{ ev} = \frac{(4.8 \times 10^{-10} \text{ esu})\ (1 \text{ esv})}{300\ \frac{\text{esv} \times \text{esu}}{\text{erg}}}$$

$$= 1.6 \times 10^{-12} \text{ erg.}$$

The unit, Mev = million electron volts, is also used. Since

$$1 \text{ Mev} = 1.6 \times 10^{-6} \text{ erg,}$$

one amu converted to energy by $E = mc^2$ corresponds to:

$$\frac{(1.66 \times 10^{-24} \text{ gm})\ (3 \times 10^{10} \text{ cm/sec})^2}{1.6 \times 10^{-6} \text{ erg/Mev}} = 931 \text{ Mev.}$$

Units Summary

Quantity	Symbol or Formula	Dimensions	CGS Units
Mass	M, m	M	gm
Length	L, s, d	L	cm
Time	T, t	T	sec
Velocity	v	L/T	cm/sec
Acceleration	$a = \frac{v_{av}}{t}$	L/T^2	cm/sec/sec
Acceleration of Gravity	g	L/T^2	980 cm/sec^2
Weight	w = mg	ML/T^2	980m dynes
Force	F = ma	ML/T^2	$\frac{gcm}{sec^2}$ = dynes
Work	W = F·d	ML^2/T^2	$\frac{gcm^2}{sec^2}$ = ergs
Kinetic Energy	$KE = 1/2\ mv^2$	ML^2/T^2	ergs
Potential Energy	PE = mgh	ML^2/T^2	ergs
Power	P = w/t	ML^2/T^3	ergs/sec (10^7 erg/sec = watt)
Momentum	p = mv	ML/T	dyne·sec
Angular Momentum	L = mvr	ML^2/T	erg·sec

Unit	Symbol	Value in CGS
Atomic Mass Units	amu	1.66×10^{-24} gm
Electronic Charge	e	4.8×10^{-10} esu of charge
Electron Volt	ev	1.6×10^{-12} ergs
Million Electron Volt	Mev	1.6×10^{-6} ergs

1 amu converted to energy = 931 Mev

56. SUMMARY

The reason for stressing units and basic dimensions of physical quantities is that problems are often more easily solved if proper units are used. The various units may be canceled just like ordinary numbers in the formulas, and the answer to a problem will have the units left after cancellation. As an example, find the velocity of a particle which has a certain energy E; let E = 120 ev, mass of particle = 4 amu. It is known that

$$\frac{1}{2} mv^2 = \text{energy} = E$$

$$\text{therefore } V = \sqrt{\frac{2E}{m}}$$

Substituting numbers with units and canceling units to make sure the correct units are obtained for the answer results in the following:

$$V = \sqrt{\frac{(2)\ (120\ \text{ev}) \left(1.6 \times 10^{-12}\ \frac{\text{ergs}}{\text{ev}}\right) \left(1\ \frac{\text{gm cm}^2}{\text{sec}^2}/\text{erg}\right)}{(4\ \text{amu})\ (1.66 \times 10^{-24}\ \text{gm/amu})}}$$

$$= \sqrt{\frac{(2)\ (120)\ (1.6)\ 10^{-12}}{(4)\ (1.66 \times 10^{-24})} \left(\frac{\text{cm}^2}{\text{sec}^2}\right)} = 7.6 \times 10^6\ \frac{\text{cm}}{\text{sec}}.$$

The student always should remember to keep units in the problem until the end, to avoid mistakes in unit conversions, and to avoid forgetting to square or perform some other essential mathematical operation.

SECTION III. ATOMIC STRUCTURE

57. GENERAL

In order to understand various atomic energy principles, a basic knowledge of the structure of atoms is necessary. In this section, a few fundamental concepts of atomic structure will be introduced. After a historical introduction, the Bohr theory and its more modern extensions will be discussed, and an explanation will be given on how this theory will account for the building up of atoms as illustrated in the periodic table of the elements.

58. HISTORY

a. Among the writings of the ancient Greeks, references are found to atoms, or indivisible particles as the ultimate building blocks in all matter. Democritus apparently first suggested it, and Lucretius followed his belief. Their idea was that different materials differed in sizes, shapes, and colors of these atoms; vinegar, for example, having sharp atoms, and sugar having smoother round ones. These ideas were essentially philosophical speculation, as was much early Greek thinking, and bears no real relation to present day atomic concepts. Aristotle and most other Greek philosophers did not approve of the atomists and tended instead toward a 4-element theory, in which earth, air, fire, and water were the basic constituents of all matter. Differences in materials were considered to be due to different proportions and different modes of mixing the basic four elements.

b. During the middle ages, these ideas about matter were largely neglected, except for the few alchemists who attempted to change lead to gold by magical superstitions and the few known chemical principles. They based their hopes on the 4-element theory, trying to change the proportions and mixing of the earth, air, fire, and water in lead to those of gold or precious stones.

c. The renaissance of arts and sciences saw an increased interest in experimentation as a means of understanding nature. Galileo dropped weights from the leaning tower of Pisa. Other early scientific developments led researchers to abandon the earth-air-fire-water theory in favor of some kind of atomistic concept. The final deathblow to the old idea was dealt by the discovery that water could be broken up into two gases, oxygen and hydrogen.

d. In the early 1800's, several different people experimented with gases, and the evidence piled up in favor of a kinetic theory of matter. From the observed gas pressure, temperature, and volume laws; and from the way in which various gases combined and decomposed chemically in the laboratories, it was deduced that small molecules were the ultimate particles of matter. Hydrogen was found to have the lightest molecules, and one scientist suggested that all other molecules were made up of basic hydrogenic molecules as building blocks.

e. The first decisive experimental proof of the early kinetic theory was provided by Brownian motion. See paragraph 26. From the motion of colloidal particles in liquid suspensions, the approximate masses of molecules were determined, and these data agreed well with the values from gas laws and chemical research. The random

Brownian motion of suspended particles provides a striking demonstration of the existence of these invisible constituents of all matter.

59. DEFINITIONS

It is now time in this discussion to define some of the basic concepts in chemistry and atomic physics. These concepts began to be accepted in science during the 19th century.

a. An element may be defined as a substance which cannot be separated into substances different from itself by ordinary chemical means.

b. A compound is a chemical combination of different substances; e.g., sugar, water, salt.

c. A mixture is a physical mixture of different substances without their chemical combination; e.g., face powder.

d. A molecule is the smallest quantity of a substance which will normally exist by itself and retain all the chemical properties of the element or substance.

e. An atom is the smallest particle of an element which still retains all the characteristics of the element.

f. Chemical reactions are processes by which the atoms in various reacting molecules rearrange, or reattach themselves; and in this process, they may consume or release small amounts of energy in the form of heat or electrical energy. The burning of coal, oxidation, is an example of chemical reaction. The energy comes from interatomic and intermolecular binding forces. Chemical properties are thus the characteristics of substances in their various chemical processes. Among the chemical properties of an atom is its power to combine with other atoms. The combining power or valence is a measure of how many other atoms it can bind to itself by interatomic forces. Notice that this portion of the text is not dealing with details of internal structure of atoms, but only with the binding forces an atom as a whole exerts on another whole atom.

60. AVOGADRO'S LAW

a. The next historical development in the field of atomic physics was the law of Avogadro, first stated early in the 19th century, but understood only later in the 1850's. Avogadro, with a great deal of foresight for his time, found a means of determining the relative masses of various molecules and atoms. As originally stated, his hypothesis was that "equal volumes of different gases at standard temperature and pressure conditions (0° C., 1 atmosphere) contain equal numbers of molecules." The relative masses of molecules are then determined by measuring the relative gaseous densities of substances. Measurements of certain volumes of various gases (22,400 cc.) give the following data for relative masses:

Element	Symbol	Wt. of 22,400 cc. at 0° C., 1 atmosphere pressure	Relative Atomic Wt.
Hydrogen	H_2	2.02	1.01
Helium	He	4.00	4.00
Nitrogen	N_2	28.02	14.01
Oxygen	O_2	32.00	16.00
Fluorine	F_2	38.00	19.00
Neon	Ne	20.18	20.18
Chlorine	Cl_2	70.92	35.46
Argon	A	39.94	39.94

Since many gas molecules contain two atoms, for example, H_2, N_2, O_2, F_2, Cl_2, their weights of 22,400 cc. have been divided by 2, in order to get the relative atomic weights of these gases. It is convenient to take the weight of an oxygen molecule O_2 as 32.0000, and of an oxygen atom as 16.0000 for a relative standard. This choice gives the lightest gas, hydrogen, an approximate atomic weight of 1.0. Also, oxygen is an easy gas to handle chemically in a laboratory and is a better standard than hydrogen, for example, for this practical reason. Therefore, an average oxygen atom is defined as having a mass of 16.0000 atomic mass units; and all other atomic weights are given relative to this value.

b. An amount of a gas which weighs its relative molecular weight in grams (i.e., 32 gm of O_2, or 2.02 gm of H_2, etc.) is called a gram-molecular-weight or mole of this gas. At standard temperature and pressure conditions, this amount of any gas occupies 22,400 cc. volume. According to Avogadro's law then, a gram-molecular-weight of any gas contains the same number of molecules. This number, N_o, is called Avogadro's Number, and is measured at 6.02×10^{23} molecules. Another way of defining a gram-molecular-weight is that amount of substance containing 6.02×10^{23} molecules. This concept should be well understood.

c. The gram-molecular-weight concept has been extended to include materials where single atoms are the normal, basic, smallest particle, such as most nongaseous elements, and the noble gases, such as helium and argon. A gram-atomic-weight (gaw) of a substance is that amount of material (1) which weighs in grams the relative atomic weight; and (2), which contains 6.02×10^{23}, Avogadro's number, of atoms. If the distinction between atoms and molecules is understood, the distinction between gram-atomic and gram-molecular weights should also be clear.

d. A problem will be worked to illustrate the gram-atomic-weight (gaw) concept. Given that iron has a relative atomic weight of 55.85, how many grams constitute a gaw? Answer: 55.85 grams. How many gaw in 200 gm of iron? Answer:

$$\frac{200}{55.85} = 3.58 \text{ gaw.}$$

How many iron atoms in 200 gm of iron? Answer:

$$(3.58 \text{ gaw}) \left(6.02 \times 10^{23} \frac{\text{atoms}}{\text{gaw}}\right) = 21.5 \times 10^{23} = 2.15 \times 10^{24} \text{ atoms.}$$

61. PROBLEMS

The student should work the following problems:

a. Given relative atomic weight of Be is 9.013, how many atoms in 2 grams of Be?

b. Given relative atomic weight of hydrogen is 1.008, how many atoms in 2 grams of H? In 1 gram? What is the mass in grams of one H atom? If H_2 is the formula for a hydrogen molecule, how many molecules in 2 grams of H_2? What is mass in grams of an H_2 molecule?

c. How many grams of cadmium (atomic weight 112.4) would be needed to comprise 8×10^{25} atoms?

62. MENDELJEEF'S CHART

a. In 1858, a Russian named Mendeljeef made a tabular arrangement of all the elements then known, and this table demonstrated a periodic law of chemical properties. He grouped the elements with similar valences in columns, and in rows according to their atomic masses. With a few exceptions, this procedure worked out well in the table. When gaps appeared in the table, he left them as gaps, assuming that other elements were yet to be discovered which would fill the gaps. On this basis, he was able to predict closely the properties of several undiscovered elements; and when these were discovered and found to have the predicted chemical properties, the periodic table was accepted widely as a correct classification system.

b. Figure 10 presents a modern version of this periodic table. The relative atomic mass of each element is listed under the symbol. The importance of this table will be apparent later, when a study is made of the actual structure of atoms. However, a few things can be learned now from the table.

(1) Since chemical reactions involve only interactions between outer parts of the atoms taking part, the similar properties of different elements must represent some kind of similarity in outer atomic structure. For example, notice in column I, Li (lithium), Na (sodium), K (potassium), Rb (rubidium), and Cs (cesium). These elements are all chemically similar in being extremely reactive, in forming strongly basic hydroxides, and in having valence +1. In column II, Be, Mg, Ca, Sr, Ba, and Ra all have normal valence +2, form hydroxides, and have other similar chemical properties. In column VII, fluorine, chlorine, bromine, and iodine show similar properties chemically. In column VIII, He, Ne, A, Kr, Xe, and Rn are all inert and do not react chemically. Other columns show corresponding similarity between elements. It, therefore, may be concluded that the outermost structures of atoms of elements in a given column are similar.

(2) The rows become longer for the heavier element end of the table. There are 8 elements between the similar helium and neon; again 8 between neon and argon; but 18 between argon and krypton, and 18 between krypton and xenon; then 32 between xenon and radon. This fact implied that the inner structure of atoms increases in size with the larger atoms, even though the outer details may be similar to that of smaller atoms. These deductions from the periodic table will be justified later.

63. RUTHERFORD'S ATOM

a. Toward the end of the 19th century, electricity began to be

	I	II	III	IV	V	VI	VII	VIII			0
1	1 H HYDROGEN 1, 2, 3										2 He HELIUM 3, 4
2	3 Li LITHIUM 6, 7	4 Be BERYLLIUM 9	5 B BORON 10, 11	6 C CARBON 12, 13, 14	7 N NITROGEN 14, 15	8 O OXYGEN 16, 17, 18	9 F FLUORINE 19				10 Ne NEON 20, 21, 22
3	11 Na SODIUM 23, 24	12 Mg MAGNESIUM 24, 25, 26	13 Al ALUMINUM 27	14 Si SILICON 28, 29, 30	15 P PHOSPHORUS 31	16 S SULPHUR 32, 33, 34, 36	17 Cl CHLORINE 35, 37				18 Ar ARGON 36, 38, 40
4	19 K POTASSIUM 39, 40, 41	20 Ca CALCIUM 40, 42, 43, 44, 46, 48	21 Sc SCANDIUM 45	22 Ti TITANIUM 46,47,48,49,50	23 V VANADIUM 51	24 Cr CHROMIUM 50, 52, 53, 54	25 Mn MANGANESE 55	26 Fe IRON 54,56,57,58	27 Co COBALT 59, 60	28 Ni NICKEL 58, 60, 61, 62, 64	
	29 Cu COPPER 63, 65	30 Zn ZINC 64, 66, 67, 68, 70	31 Ga GALLIUM 69, 71	32 Ge GERMANIUM 70, 72, 73, 74, 76	33 As ARSENIC 75	34 Se SELENIUM 74, 76, 77, 78 80, 82	35 Br BROMINE 79, 81				36 Kr KRYPTON 78, 80, 82, 83 84, 86, 87
5	37 Rb RUBIDIUM 85, 87	38 Sr STRONTIUM 84, 86, 87, 88	39 Y YTTRIUM 89	40 Zr ZIRCONIUM 90, 91, 92, 94, 96 95, 97, 98	41 Nb NIOBIUM 93, 95, 97	42 Mo MOLYBDENUM 92, 94, 95, 96, 97 98, 99, 100	43 Tc TECHNETIUM 97, 99	44 Ru RUTHENIUM 96, 98, 99, 100, 101 102, 104	45 Rh RHODIUM 103	46 Pd PALLADIUM 102, 104, 105, 106, 108 110, 118	
	47 Ag SILVER 107, 109, 110	48 Cd CADMIUM 106, 108, 110, 111, 112 113, 114, 116	49 In INDIUM 113, 115	50 Sn TIN 112, 114, 115, 116, 117, 118, 119, 120, 122, 124	51 Sb ANTIMONY 121, 123	52 Te TELLURIUM 120, 122, 123, 124, 125 126, 128, 130, 137, 138	53 I IODINE 126, 137				54 Xe XENON 124, 126, 128, 129, 130 131, 132, 134, 136, 137
6	55 Cs CESIUM 133, 137	56 Ba BARIUM 130, 132, 134, 135, 136 137, 138, 140	RARE EARTHS 57 – 71 (See Below)	72 Hf HAFNIUM 174, 176, 177, 178, 179, 180	73 Ta TANTALUM 181, 182	74 W TUNGSTEN 180, 182, 183, 184, 186	75 Re RHENIUM 185, 187	76 Os OSMIUM 184, 186, 187, 188, 189 190, 192	77 Ir IRIDIUM 191, 193	78 Pt PLATINUM 192, 194, 195, 196, 198	
	79 Au GOLD 197	80 Hg MERCURY 196, 198, 199, 200, 201, 202, 204	81 Tl THALLIUM 203, 205	82 Pb LEAD 204, 206, 207, 208	83 Bi BISMUTH 209, 210	84 Po POLONIUM 208, 210	85 At ASTATINE 215, 218				86 Rn RADON 219, 220, 222
7	87 Fr FRANCIUM 223	88 Ra RADIUM 223, 224, 226, 228	RARE EARTHS 89 - 103 (See Below)	104							

RARE EARTHS (LANTHANIDES)	57 La LANTHANUM 138, 139, 140	58 Ce CERIUM 136, 138, 140, 141, 142	59 Pr PRASEODYMIUM 141	60 Nd NEODYMIUM 142, 143, 144, 145, 146, 148, 150	61 Pm PROMETHIUM 147	62 Sm SAMARIUM 144, 147, 148, 149, 150, 152, 154	63 Eu EUROPIUM 151, 153	64 Gd GADOLINIUM 152, 154, 155, 156, 157, 158, 160	65 Tb TERBIUM 159	66 Dy DYSPROSIUM 156, 158, 160, 161, 162, 163, 164	67 Ho HOLMIUM 165	68 Er ERBIUM 162, 164, 166, 167, 168, 170	69 Tm THULIUM 169	70 Yb YTTERBIUM 168, 170, 171, 172, 173, 174, 176	71 Lu LUTETIUM 175, 176

RARE EARTHS (ACTINIDES)	89 Ac ACTINIUM 227, 228	90 Th THORIUM 227, 228, 229, 230, 231, 232, 234	91 Pa PROTACTINIUM 231, 233, 234	92 U URANIUM 233, 234, 235, 238, 239	93 Np NEPTUNIUM 237, 239	94 Pu PLUTONIUM 237, 238, 239, 240, 241	95 Am AMERICIUM 241, 242	96 Cm CURIUM 242	97 Bk BERKELIUM 243	98 Cf CALIFORNIUM 244	99	100	101	102	103

All isotopes found in nature are listed
A few of the artificially produced isotopes are listed

Radioactive isotopes are underlined 239

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Figure 10. Periodic Table of the Elements

understood, and it was found that atoms were composed of electrically charged bits of matter. In a neutral atom, equal amounts of positive and negative electricity are stuck together, but until 1911 it was not known just how the charge was arranged. It was known that the negative charges were very light and mobile, and that they were responsible for the conduction of electricity. They had been called electrons for some time. It was also known that heavy, positively charged particles would spontaneously be ejected from certain atoms in the radioactivity process. These were called α particles and were shown to be helium atoms which had lost their negative charge (i. e., doubly ionized He). In 1911, Rutherford showed that the atom is built of two basic parts, a small but heavy positive nucleus, and a light negative cloud of extranuclear charge. Figure 11 shows the Rutherford atomic picture.

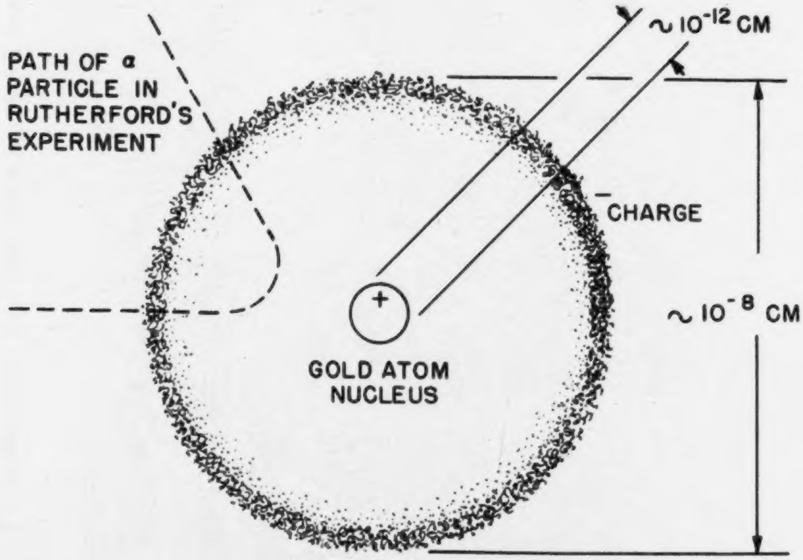

Figure 11. Rutherford's Atom

b. This model was arrived at by experimentation. α particles from radium bombarded a thin gold foil. Most of them passed through with only slight deflection, but some were deflected by large angles--up to 180 degrees. This fact could only be interpreted as a process in which these α particles struck a heavy, positively charged bit of matter. From these and other scattering experiments, the relative sizes and masses of the nucleus and the electronic cloud were calculated. Almost all the mass of the atom is concentrated in the nucleus, which has a diameter of about 10^{-12} cm. The diameter of the whole atom, the electron cloud, is about 10^{-8} cm.

64. BOHR'S ATOM

a. By the first decade of the 20th century, physicists were in possession of a great mass of data regarding atomic phenomena, but without a really comprehensive theoretical interpretation of it. Among the more significant of these facts was the spectroscopic data on the nature of light emitted from various substances. If the light from electrical discharges in gases or from incandescent material is analyzed into its component wavelengths by a prism or other spectrograph, a series of definite colored lines is found. Each element is characterized by its own spectral lines. In some cases, a series of lines with regular spacings occur on a spectrograph. See figure 12.

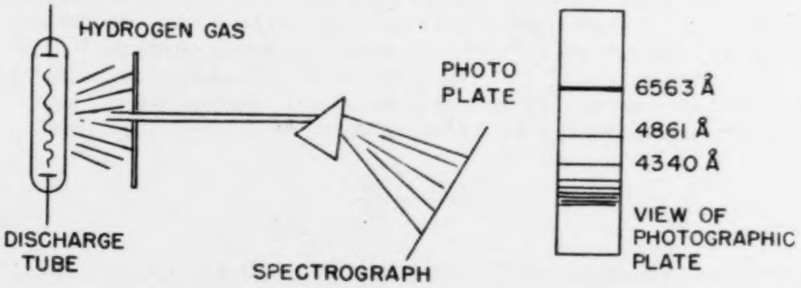

Figure 12. Spectrography

With sodium, two closely-spaced lines were found at 5890 Å and 5896 Å. With hydrogen, several series of lines were found with wavelengths varying from ultraviolet to infrared. These discrete spectral lines suggested that atoms were so constructed that light was emitted in definite amounts of energy when the atoms were excited.

b. As early as 1903, Planck had shown that electromagnetic radiation could be thought of as being absorbed and emitted in discrete quanta, with energy $E = h\nu$. See paragraphs 41 and 52. Also, the photoelectric effect, interpreted by Einstein in 1908, demonstrated that light of various wavelengths had various energy quanta, or photons, as postulated by Planck; and that light intensity did not depend on the energy of the photons, but upon the number of photons. It was a consideration of such facts as these that led Bohr to make three postulates for a new theory in 1913.

c. Bohr assumed a nuclear atom, as has been discussed. He postulated:

I. The electrons outside the nucleus exist in stable circular orbits.

II. The angular momentum of an electron in its orbit may assume only certain definite values, integral multiples of $h/2\pi$, (i.e., angular momentum = $nh/2\pi$, where $n = 1, 2, 3$, or other whole number; n is called the principal quantum number.)

III. Light is emitted or absorbed in transitions or quantum jumps between the various orbits.

d. The first postulate was hard for some classical physicists to accept, since it stated that the accelerated electron need not radiate energy as required by the classical radiation theory of Maxwell. In the Bohr theory, the electron is centripetally accelerated without losing any of its energy. From this postulate, a relation may be set down between the forces acting on the electron of a hydrogen atom:

$$\frac{mv^2}{r} = \frac{e^2}{r^2}.$$

In the above equation, mv^2/r is the centrifugal force, e^2/r^2 is the electrostatic attractive force, and these two forces must balance if a stable orbit is to exist.

e. The second postulate is the quantization rule by which the discrete quantum nature of the theory is introduced. Mathematically,

$$mvr = \frac{nh}{2\pi}.$$

Here mvr is the angular momentum of the electron in an orbit of radius r. The quantization rule is responsible for the fact that the possible orbits have only certain specific radii. To each orbit, there corresponds a certain total energy of the atom, which is the energy level of the atom.

f. The third postulate explains how radiation is emitted. The atom may be put into an energy level of higher than normal energy by

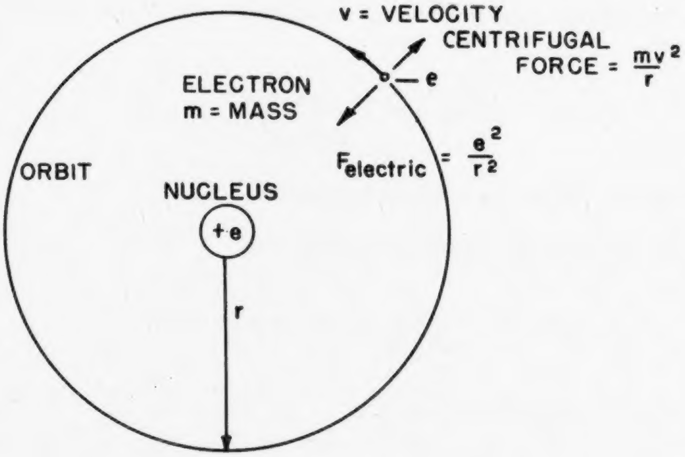
v = VELOCITY
CENTRIFUGAL FORCE = $\frac{mv^2}{r}$
ELECTRON
m = MASS
— e
ORBIT
NUCLEUS
+e
$F_{electric} = \frac{e^2}{r^2}$
r

Figure 13. Bohr's Atom

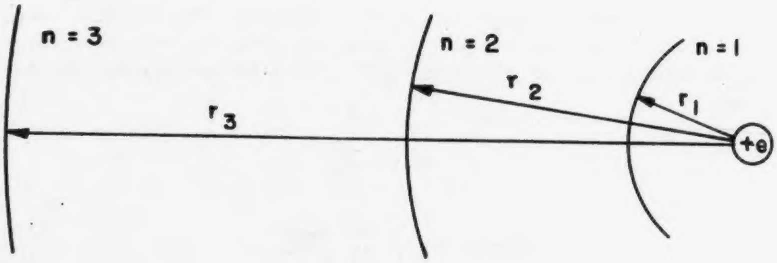
n = 3
n = 2
n = 1
r_3
r_2
r_1
+e

Figure 14. Orbit Radius

some means. Then as it jumps back to a lower energy level, radiation is emitted. The frequency ν of the emitted light is given by:

$$h\nu = W_{initial} - W_{final}$$

where $W_{initial}$ is the energy of the higher level, and W_{final} is the lower energy level.

g. Algebraic manipulation of postulates I and II leads to the expression:

$$r_n = n^2 \left(\frac{h^2}{4\pi^2 me^2} \right)$$

for the radius of the nth orbit in hydrogen.

From the information contained in figure 14,

$$r_1 = 1^2 \left(\frac{h^2}{4\pi^2 me^2} \right) = 5.29 \times 10^{-9} \text{ cm.}$$

$$r_2 = 2^2 (r_1) = 4r_1$$

$$r_3 = 9r_1$$

Note that the orbit radius increases rapidly for the higher energy levels.

h. The total energy of the hydrogen atom, when its electron is in an orbit n, is partly kinetic and partly potential. The kinetic energy comes from the motion of the electron, the potential energy from its position in the nucleus' electric field. The total energy may be written as:

$$W = - \frac{e^2}{2r}.$$

$$\text{Thus: } W_n = \frac{2\pi^2 \ me^4}{h^2 n^2}.$$

The minus sign indicates binding; that is, work must be done to separate the electron from the nucleus. An energy level diagram is often plotted to illustrate the atom.

i. The student should notice that these are the only possible energies for the atom to have, and that the atom is in only one level at a time. Obviously it could not possess 2 energies at once, nor could 1 electron be in 2 orbits at once. For a given value of n, however, the energy is a certain definite amount.

j. From this energy level diagram, which shows energy as a

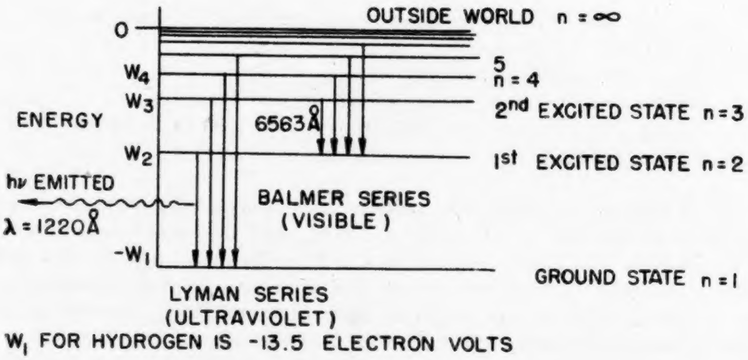
0
W4
W3
ENERGY
W2
hν EMITTED
λ = 1220Å
-W1
6563Å
OUTSIDE WORLD n = ∞
5
n = 4
2nd EXCITED STATE n=3
1st EXCITED STATE n=2
BALMER SERIES
(VISIBLE)
GROUND STATE n=1
LYMAN SERIES
(ULTRAVIOLET)
W1 FOR HYDROGEN IS -13.5 ELECTRON VOLTS

Figure 15. Energy Level Diagram

function of n, the processes of emission or absorption of light, as discrete quanta, may be seen. The lowest state of the atom is the normal one, the ground state, n = 1. If the atom is excited to a higher state, say n = 2, a transition from n = 2 to n = 1 may occur in which light energy is emitted. The frequency ν is given by:

$$\Delta E = h\nu = W_{initial} - W_{final}$$

$$= \frac{2\pi^2 me^4}{h^2}\left(\frac{1}{n_f{}^2} - \frac{1}{n_i{}^2}\right) = \frac{2\pi^2 me^4}{h^2}\left(\frac{1}{1^2} - \frac{1}{2^2}\right).$$

In general, for a transition from n_i to n_f, the wavelength λ of the radiation involved is given by

$$\frac{1}{\lambda} = \frac{\nu}{c} = \frac{2\pi^2 me^4}{ch^3}\left(\frac{1}{n_f{}^2} - \frac{1}{n_i{}^2}\right)$$

$$= 1.09 \times 10^5\left(\frac{1}{n_f{}^2} - \frac{1}{n_i{}^2}\right)\ \mathrm{cm}^{-1},$$

where 1.09×10^5 is called R, the Rydberg constant. For example, the wavelength of light emitted in transition n = 2 to n = 1 is 1220 Å.

$$\frac{1}{\lambda} = 1.09 \times 10^5\left(\frac{1}{1} - \frac{1}{4}\right) = 0.817 \times 10^5\ \mathrm{cm}^{-1}$$

$$\lambda = 1220\ \text{Å}$$

k. A spectral series results from a series of transitions which all end on the same level. The series of transitions, 2 to 1, 3 to 1, 4 to 1, etc., give a series of ultraviolet spectral lines called the Lyman series. The transitions ending on level n = 2 (i.e., 3 to 2, 4 to 2, 5 to 2, etc.) give the Balmer series, which is in the visible region of the spectrum.

l. In this connection, the student should again be reminded that 1 atom may be in only 1 state at a time, and therefore a single atom may make only 1 transition at a time. The observed series of lines are the quadrillions of atoms which are all being excited simultaneously to various levels and making various transitions, resulting in photons of a large number of different wavelengths. In other words, the laboratory experiment is done with large numbers of atoms, and statistical behavior is to be expected.

m. Absorption of light takes place by the transition of an atom from a lower to a higher energy level. This fact explains the discrete absorption spectra, and the fact that light is absorbed in quanta.

n. The results of the Bohr quantum theory of the atom will now be summarized. The hydrogen atom was pictured as a miniature solar system with a heavy positive nucleus and a light negative satellite electron which could assume only certain radii. These possible radii of orbits were governed by the quantum condition, and a definite total energy of the atom was associated with each possible orbit. Thus, the atom is described as being in a certain state, depending on the principal quantum number n. The most stable state is the ground state, having the lowest energy. Excited states may also exist, if some means is provided to add sufficient energy to the atomic system. When a transition occurs between states, a photon of light energy may be involved. If an atom in an excited state relaxes into a lower energy state, the difference in energy of the two states is emitted as a light quantum. This explains line spectra. An atom in a ground state may absorb a quantum of the proper energy and go into an excited state. This explains absorption phenomena. If the electron is kicked out of the atom entirely, it has been excited to $n = \infty$ and the atom is said to be ionized. The energy of an ionized state is taken as zero on the energy level diagram, since the free electron feels no force on it from the nucleus. The bound states of the electron all possess a negative energy on the diagram, with the ground state having the most negative energy since it is most tightly bound.

65. BOHR'S THEORY EXTENDED

a. The Bohr picture accounted for most of the 1913 facts, but it could not give a good explanation for any but hydrogen-like (one electron) atoms. Nor could it explain the relative intensities of spectral lines; that is, the relative probabilities of different possible transitions. Another inadequacy was that it did not explain the *fine structure* of spectral lines. By this is meant that often 2 or 3 spectral lines are grouped very closely on the spectrograph, so that they appear as 1 line on any but the most sensitive equipment. This structure of a spectral line implied that the energy levels in the Bohr theory were not simply one state, but were actually split into several closely lying energy states.

b. In the years following 1913, these inadequacies were investigated, and Bohr's theory was extended. Elliptical orbits were postulated, and these were found to give sufficient variations in level energies to allow for some of the observed fine structures. Another approach was to assume that the electron was spinning on its own axis with an intrinsic angular momentum,

$$h/4\pi \left(\frac{1}{2} \times \frac{h}{2\pi}\right).$$

This *spin angular momentum*, or *spin*, then introduced a small amount of magnetic moment into the atom, and interaction of this spin magnetic moment and the magnetism generated by the orbital electronic motion was sufficient to account for the level splitting. In this new theory, with spin, the total angular momentum was required to be quantized. If j is total angular momentum quantum number, $j = l + s$, where l is orbital and s is the spin-quantum number. It was found that:

$$s = \pm \frac{1}{2},$$

and l could be any integer up to n, the principal quantum number. This model[1] of the atom accounted for many phenomena, including two electron atoms, Zeeman and Start[2] effects, level splittings, and some of the transition probabilities; but of course several new quantum numbers were introduced as well. These numbers, n, l, j, s, were brought into the theory in a quite empirical way, to explain observations.

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[1] The *vector* model of the atom.

[2] Zeeman effect is the splitting of spectral lines when the atom is in a magnetic field. Stark effect is the same for an electric field.

66. QUANTUM MECHANICS [1]

a. Entirely different approaches to the subject of atomic theory were made independently by Schroedinger and Heisenberg. The resulting theory, called quantum mechanics, is a statistical one. It accounts for transition probabilities between states, for the small differences in energy of close lying states; in short, for the correct prediction of all observable physical quantities. The quantum numbers arise quite naturally in this theory and do not result simply from arbitrary assumptions regarding atomic structure. However, no real picture of an atom is given by quantum mechanics as it was given by Bohr's theory.

b. Several quantum numbers arise naturally from the new quantum theory. They are n, the principal quantum number; l, the orbital angular momentum quantum number; m, the magnetic quantum number, which describes the splitting of energy levels when a magnetic field is applied to an atom; and s, the electron spin quantum number. The following table shows the allowed values for these numbers:

$n = 1, 2, 3, 4, \dots$ any integer

$l = 0, 1, 2 \dots n - 1$, integers up to, but not including n.

$m = -l, -l + 1, \dots 0, 1, 2 \dots l$, all integers, positive and negative between $-l$ and $+l$.

$s = \pm\frac{1}{2}$.

c. Each possible state of an atomic system is thus characterized by a set of four numbers, n, l, m, s. The ground state of hydrogen, for example, is given by:

$n = 1$ $\quad$ $m = 0$

$l = 0$, $\quad$ $s = +\frac{1}{2}$ or $-\frac{1}{2}$.

Excited states, with the electron in a larger orbit, will be given by larger n values. The first excited state in hydrogen has $n = 2$. Then there are possible variations in energy of this state, corresponding to $l = 0$ and $l = 1$. For $l = 0$, $m = 0$, and $s = \pm 1/2$. For $l = 1$, $m = -1$, 0, or +1, with $s = \pm 1/2$ possible in each state. This means there could be six separate splittings in the energy level $n = 2$. Transitions from these various split levels to the ground state cause fine structure in the spectra.

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[1] Paragraphs 65 and 66 are presented for the benefit of those students interested in additional information on this subject and are not presented in the formal course of instruction.

67. HOW ATOMS ARE BUILT

a. It has been mentioned that the newer quantum theory allows a description of atoms with more than one electron. This will not be attempted here with all the mathematical apparatus of the new theory. Rather, this text will use the Bohr picture and borrow only the quantum numbers from the modern theory. Only the ground states of the various atoms will be considered.

b. A hydrogen atom has a positively charged nucleus and a single electron. In its ground state then, it must look something like figure 16.

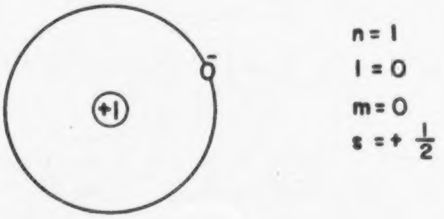

Figure 16. Hydrogen Atom

$s = +1/2$ indicates that the electron spin vector is parallel to the orbital angular momentum vector.

c. To make a helium atom requires 2 positive charges on the nucleus, as well as some additional mass there, and 2 orbital electrons. They may arrange in the ground state like figure 17.

d. To make a lithium atom, 3 charges on the nucleus are needed, plus more mass and 3 electrons. One might think that the third electron could have $n = 1$ for its lowest energy, but a basic principle of quantum mechanics must be evoked: No two electrons may have the same identical set of quantum numbers. This is the Pauli exclusion principle. It shows that in a lithium atom the third electron cannot

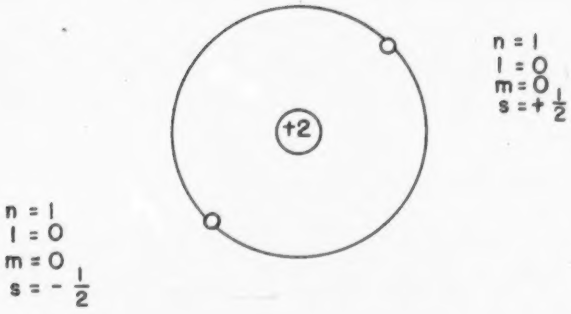

Figure 17. Helium Atom

have n = 1, but must be in an n = 2 state. The ground state of lithium thus may be pictured as in figure 18.

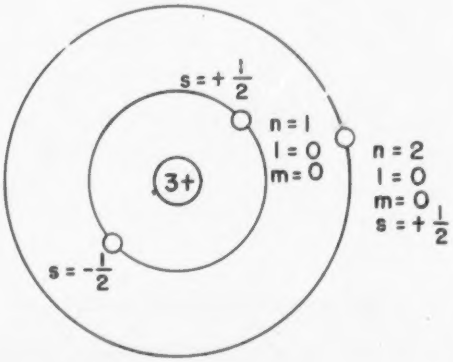

Figure 18. Lithium Atom

e. To make a beryllium atom, a positive charge and some mass must be added to the nucleus and an electron to the n = 2 shell. See figure 19.

f. To make boron, a fifth charge plus mass is added to the nucleus, and a fifth electron is placed in the outer structure. The n = 2 and l = 0 states are used up, but n = 2 with l = 1 states are available, so the boron atom in its ground state looks something like figure 20.

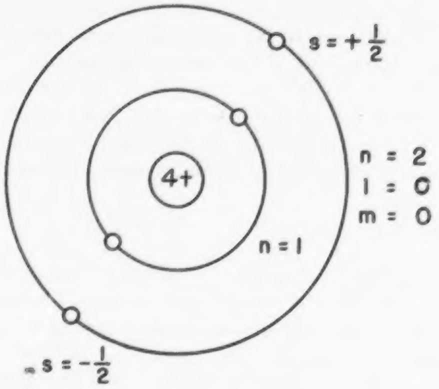
s = + $\frac{1}{2}$
4+
n = 2
l = 0
m = 0
n = 1
s = − $\frac{1}{2}$

Figure 19. Beryllium Atom

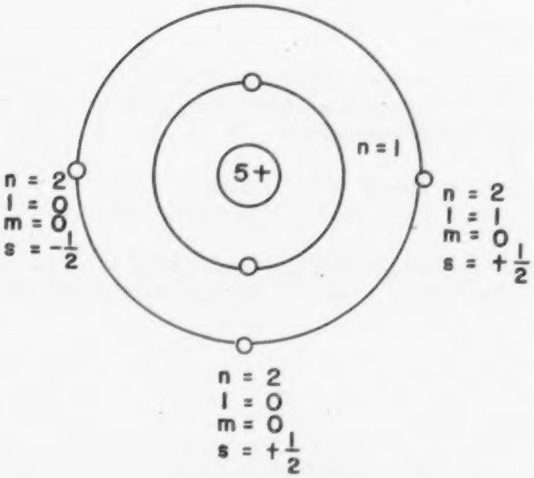
n = 1
5+
n = 2
l = 0
m = 0
s = − $\frac{1}{2}$
n = 2
l = 1
m = 0
s = + $\frac{1}{2}$
n = 2
l = 0
m = 0
s = + $\frac{1}{2}$

Figure 20. Boron Atom

g. As an upward progression is made in the periodic table, it is found that electrons continue to be added in conformity with the exclusion principle. The periodicity of chemical properties is explained by the similarity in outermost electron configurations. The chemical inertness of certain elements is explained by the completed shells of electrons which tend not to lose or to add electrons. The longer periods in the table are explained by the filling of inner shells with more and more electrons as the size of the atoms increases.

68. SUMMARY

The student should remember Bohr's three postulates, the general outline of the old Bohr theory, and the success it had in explaining various phenomena. He should recognize its inadequacies and how the newer theory obviates them. He should be familiar with the periodic table and understand in general terms why the elements may be so grouped. He should know what the various terms, atom, element, chemical property, atomic weight, and gram atomic weight mean; and be able to do problems with gram atomic weights which require calculation of the numbers of atoms in given amounts of material. He should remember that the preceding section has dealt only with the electrons in the atom. The next section will be devoted principally to basic nuclear structure.

69. PROBLEMS

a. Using the periodic chart, find how many grams of bismuth are in 1.8-gram atomic weights. How many atoms? How many electrons are in this amount of material?

b. How many atoms are in 1 cubic centimeter of aluminum which has a density of 2.7 gm/cm^3? How many electrons per cm^3?

c. What wavelength of light is admitted in a hydrogen atom quantum jump from $n = 3$ to $n = 2$? In what part of the spectrum does it lie?

CHAPTER 4

NUCLEAR PHYSICS

SECTION I. NUCLEAR STRUCTURE

70. GENERAL

The last section described in some detail the electronic configurations in atoms. While these considerations are interesting and occupied physicists' attention for many years, the detailed results are not as useful in this course as the general picture. Chemical and light photon energies are generally low and in the electron-volt range, while nuclear energies are in the Mev range. This text is more concerned with the larger nuclear energies. This section will deal with basic nuclear structure and will apply some of the quantization concepts to introduce nuclear phenomena.

71. ATOMIC NUMBERS AND MASS UNITS

a. At the turn of the century, it was discovered that many substances spontaneously emitted various types of rays. These radiations were shown to come from the nuclei of atoms. By careful experimentation and some good fortune, it was found that a few atoms actually could be transmuted or changed by allowing certain of these radiations to bombard them. It was shown that hydrogen nuclei, or protons, are responsible for the positive charge present on all nuclei. Thus, in a sense, the guess in the early 1800's that all matter is made up of hydrogen atoms was shown to be correct. However, it was known that more mass units than charge units were present in nuclei. At first it was thought that a proton and an electron were neutralized within the nucleus to provide mass without charge. It is known today that this is not so.

b. In 1932, Chadwick found a very penetrating radiation in certain nuclear experiments. He correctly attributed this to a new particle, neutral in charge, and with a mass about equal to a proton mass. This particle he named the neutron.

c. It is now known that the atomic nucleus contains two types of particles, protons and neutrons. Protons carry a unit positive electric charge and have a mass of 1.00758 amu. Neutrons carry no charge and have a mass of 1.00894 amu. These two types of particles are bound together by nuclear forces.

d. In the discussion of the periodic table, it was stated that originally Mendeljeef had ordered the elements according to their relative atomic weights. This ordering gave several irregularities in the chemical properties. For example, argon is heavier than potassium, and this inert gas should correspond to an active metal if the mass order is used. In 1914, the correct way to order the periodic table was shown by Moseley to be by the number of protons in the nucleus, not by its total mass. This number is called the atomic number of the atom, and the symbol Z is used to indicate it.

e. If there are Z protons in the nucleus then there must be Z electrons in the orbits of a neutral atom. For this reason, Z is the quantity which determines the chemical properties of an element. For example, a copper atom has 29 protons in its nucleus and 29 electrons in its orbits.

f. It is known that there are more mass units than charge units in the nucleus. Since protons have about one mass unit each, neutrons must also exist in the nucleus which have a mass unit but no charge. The total number of massive particles in the nucleus (i.e., the number of protons plus neutrons) is called the atomic mass number A of the nucleus. Thus, the number of neutrons in a nucleus with mass number A and atomic number Z is A - Z. The usual way of indicating an atom or nucleus which has atomic number Z and atomic mass A is

$$_{Z}X^{A},$$

where X is the chemical symbol for the element. For example,

$$_{29}Cu^{63},\ _{30}Zn^{65},\ _{92}U^{238},\ _{8}O^{16},$$

represent particular atoms with their atomic numbers and mass numbers specified.

72. ISOTOPES, ISOBARS, ISOMERS

a. In nature, there are many instances of an element having different atomic masses. For example, two types of copper are found,

$$_{29}\mathrm{Cu}^{63} \text{ and } _{29}\mathrm{Cu}^{65}.$$

These two types behave nearly identically, since they are both copper, with 29 protons and 29 electrons.

However, $_{29}\mathrm{Cu}^{65}$ has 36 neutrons while $_{29}\mathrm{Cu}^{63}$ has only 34 neutrons in the nucleus. These two atoms are said to be isotopes. Isotopes (from iso, meaning "same," and tope, meaning "place"; i.e., the same place in the periodic table) are atoms which have the same atomic number Z, but different atomic mass numbers, A.

$$_{9}\mathrm{F}^{17},\ _{9}\mathrm{F}^{18}, \text{ and } _{9}\mathrm{F}^{19}$$

are examples of isotopes of fluorine.

b. Atoms which have the same total number of nuclear particles but different numbers of protons are called isobars. (Baros means "weight.") Isobars have the same A, but different Z's. They are different chemical elements.

$$_{60}\mathrm{Nd}^{140},\ _{59}\mathrm{Pr}^{140},\ _{58}\mathrm{Ce}^{140},\ _{57}\mathrm{La}^{140}, \text{ and } _{56}\mathrm{Ba}^{140}$$

are examples of isobars. Isobars are important to detailed studies of nuclear theory.

c. In some cases, two atoms may have the same number of protons and the same number of neutrons, but differ in the energy level of their nuclei. Eventually the higher energy level nucleus will convert itself to a lower energy level nucleus of the same particle composition by isomeric transition. Different energy states of the same nucleus are called isomers or isomeric states of the nucleus. For example,

$$_{56}\mathrm{Ba}^{133}$$

exists in 2 isomeric forms, 1 of which decays into the other.[1]

d. The different isotopes of an element behave nearly identically in chemical reactions. Therefore, one cannot separate isotopes chemically.[1] In measuring atomic weights by chemical means, the observed value for an element will be an average value over all of its isotopes. Copper has a chemically measured atomic weight of 63.54. Natural copper occurs with 71 percent Cu-63 and 29 percent Cu-65.

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[1] This information is obtained from the Chart of the Nuclides published by the Knolls Atomic Power Laboratory, General Electric. The student would do well to examine this chart carefully, noticing isotopes, isobars, isomers, and notations.

e. The above fact has caused some confusion in the atomic weight system, since the choice of oxygen as a standard for chemical weights was made before isotopes were known. Fortunately, oxygen occurs in essentially only one isotope,[2]

$${}_8O^{16},$$

since the other isotopes, ${}_8O^{17}$ and ${}_8O^{18}$, constitute less than 0.037 percent of chemical oxygen. Therefore, the definition used so far in this book, given in paragraphs 60a and 54, is essentially correct, although physicists generally take an amu as equal to 1/16 the mass of an

$${}_8O^{16}$$

atom. Only when dealing with the fifth decimal place in calculations would the difference between the chemical and physical atomic mass scales cause any discrepancy.

73. NUCLEAR FORCES

The neutrons and protons in a nucleus are bound together very tightly by nuclear forces. These forces are stronger than the electrostatic repulsion between protons, and they exhibit several striking peculiarities:

a. Nuclear forces are short range, in that they apparently do not act except within distances of about 2×10^{-13} cm. When two nucleons (a neutron or a proton) approach each other, no nuclear force is exerted until the separation is about 2×10^{-13} cm; and at this distance the force becomes active.

b. Nuclear forces are strong; that is, they bind nucleons tightly. To separate a bound neutron and proton, as for example a H-2 nucleus, requires about 2.2 Mev of energy. To pull a neutron out of a heavier element requires up to 8 Mev. Compare this with the few ev required to remove an electron from an atom. The potential energy of a nucleon in the field of another may be as high as 25 Mev.

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[1] With certain difficult chemical techniques, using ion exchange reactions, a small degree of isotope enrichment can be accomplished. In general the statement in the text is true.

[2] This information, too, comes from the Chart of the Nuclides.

c. Nuclear forces are charge independent; that is, they act equally between proton groups, neutron groups, and proton-neutron groups.

d. Nuclear forces are attractive, but saturable; that is, a given nucleon may attract strongly up to three other nucleons, but a fourth will be repelled. This repulsion is related to the exclusion principle stated in paragraph 67d.

e. Nuclear forces are spin dependent, showing tighter binding between two nucleons whose spins are parallel than between two whose spins are antiparallel.

74. ENERGY OF THE NUCLEUS

a. An exactly correct picture of the nucleus is harder to find than one for the electronic parts of the atom. Quantum mechanical rules of thought seem to apply, but the science of detailed nuclear theory is still largely empirical. Experimenters have verified that the total energy of the nucleus is quantized; that is, restricted to certain definite values. Some evidence exists for a type of shell structure similar to the electron shells with extra stable nuclei existing with closed shells. Helium, carbon, oxygen, calcium, tin, and lead isotopes seem to show extra stable nuclear construction. Since the theory of the shell model becomes quite detailed with further description, the discussion will stop at this point. The student should know that discrete energy levels exist in the nucleus, and that these levels are not as regular or easy to describe as in the electronic levels.

b. If a nucleus is excited into any energy level other than its ground state, it will decay to its ground state with the emission of some radiation. This radiation may be a photon of electromagnetic energy, in which case it is called a gamma ray. In some cases, the nucleus will make a transition to another type of nucleus, giving up a beta particle, which may be either an electron or a positron (positive electron). In other cases, a nucleus may find itself able to get into a lower energy state by ejection of a bound group of 2 neutrons plus 2 protons, called an alpha particle, designated:

$${}_2\alpha^4 \text{ or } {}_2\mathrm{He}^{4++}$$

These three types of radioactivity were discovered long ago, but they now can be understood in terms of the energy level structure of the nucleus.

c. The nucleus can have energy transferred to it in much the same way as energy can be transferred to the orbital electrons of an atom. We are not interested in the manner in which the energy is transferred but in the fact that the nucleus can be excited and that the nucleus can remain in a metastable excited state. This excited state of a nucleus is an isomeric state.

d. The nucleus is excited to states of definite energy content much the same way as an orbital electron is excited to states of definite energy content.

e. Just as in the case of the orbital electrons, when the excited nucleus returns to a less excited state or to the ground state, electromagnetic radiation is emitted. The energy transitions for the nucleus are much greater than for the orbital electrons so that the radiation obtained is usually of higher frequency. In the case of nuclear emission, it is called gamma radiation.

f. Since the nucleus has definite, or discrete, energy states, we can construct an energy level diagram. Such an energy level diagram has been constructed for Ce-140 and is illustrated in figure 21. Due to these definite levels, the gamma ray spectrum is usually discrete; that is, there are only certain definite energies (equal to the difference between two levels) that the gammas from a given nuclide may have.

g. One important item should be noted about nuclear energy transitions as compared to electronic energy transitions. In the electronic case, the transitions are definitely associated with a definite orbital electron. Such is not the known case for nuclear energy transitions; that is, the energy levels are associated with a nucleus and not with a definite nucleon in the nucleus.

75. NUCLEAR STABILITY

a. Just why certain nuclei are more stable than others is not completely understood. However, one contributing factor is known to be the neutron to proton ratio,

$$\frac{A - Z}{Z}.$$

The n/p ratio is important to stability because of the slight tendency of protons to repel each other even though bound into a nucleus by nuclear forces. The picture of the nucleus of an atom may be thought of as being something like figure 22. Each ball represents a nucleon and its sphere of action.

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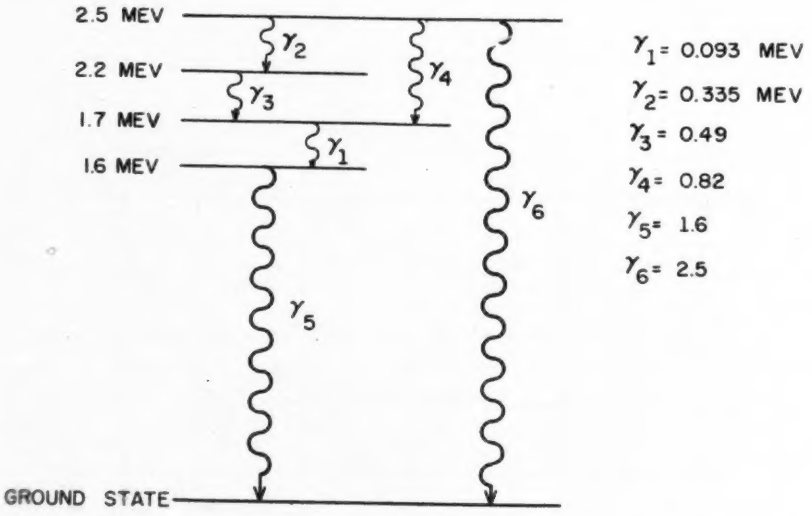
2.5 MEV
2.2 MEV
1.7 MEV
1.6 MEV
GROUND STATE
γ_1
γ_2
γ_3
γ_4
γ_5
γ_6
γ_1 = 0.093 MEV
γ_2 = 0.335 MEV
γ_3 = 0.49
γ_4 = 0.82
γ_5 = 1.6
γ_6 = 2.5

Figure 21. **Nuclear Energy Level Diagram for Ce-140**

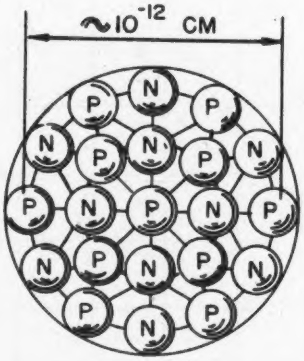

Figure 22. **Nucleus of Atom**

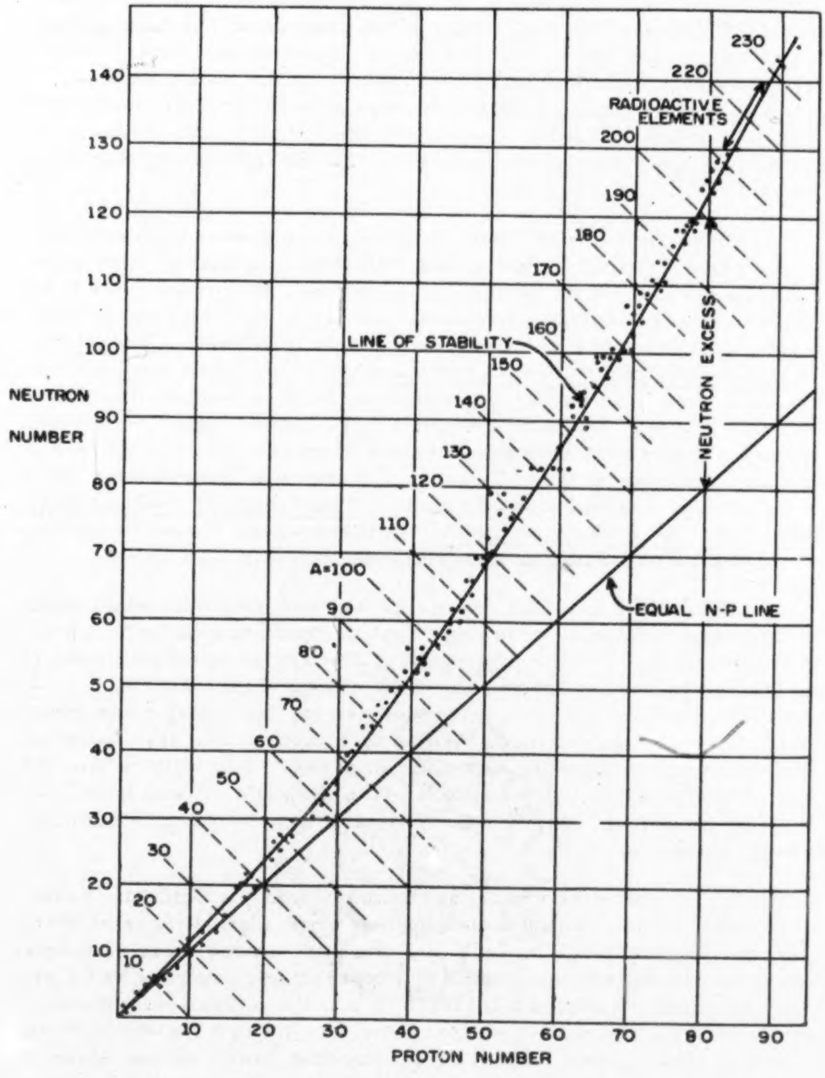

Figure 23. Nuclear Stability

Because of their charge, the protons will tend to separate from one another. However, because of saturation and spin dependence in the forces, the protons cannot all be on the nuclear surface. To take up nuclear space, then, an excess of neutrons will be required, since these particles will experience no charge repulsion, but only nuclear forces. Protons on opposite sides of the nucleus will in fact experience no direct nuclear force, but only an electrostatic force. However, they are bound nuclearly to common intermediate internal nucleons, and so the small electric repulsion is not sufficient to expel them. In other words, since the binding energy of a nucleon is greater than the electric repulsive potential energy, the nucleus stays together.

b. When there are too many protons in a nucleus, however, the nucleus generally will remain bound, but it may be that a lower energy state will exist for an isobar. In each case, the proton finds it desirable to change identity, becoming a neutron, and kicking off its charge in the form of a positive beta particle (positron). Therefore, β^+ radioactivity results from too low an n/p ratio. In a similar process, and a more common type of radioactivity, a neutron may change itself into a proton and into a negative beta particle (electron) which is ejected. This type of change results from the fact that there are too many neutrons in the nucleus, and there is a lower energy state for the isobar with a lower n/p ratio. Therefore, β^- radioactivity results from too high an n/p ratio. In these ways, a nucleus can adjust its n/p ratio for maximum stability.

c. When the n/p ratios for all the various elements which exist in nature are examined, it is found that the ratio varies from 1.0 for light elements to 1.6 for heavy nuclei. The region of stable nuclei is represented by the shaded region on the curve, figure 23. At $Z = 84$, the elements begin to be naturally radioactive, indicating some instability. If an element is made by man in a laboratory, its n/p ratio will determine its stability and mode of decay. If it falls within the region of stability, it will be stable. If to the right, it will be β^+ active; if to the left, β^- active. Gamma rays may be associated with these β emissions.

d. The α particles are most common from the naturally radioactive heavy nuclei, which indicates that their instability is at least partly due to their large mass. In α emission among these elements, the n/p ratio does not change much. Apparently 2 neutrons and 2 protons occasionally get bound together in a little mutually-exclusive group within the nucleus, then find their way out into the world as an α particle, leaving the nucleus in a somewhat lower energy state. These radioactive decay processes will be discussed more in chapter 5.

76. SUMMARY

a. The student should remember that A is the atomic mass number and indicates the total number of particles in the nucleus; that Z is the atomic number, or number of protons in the nucleus; and, therefore, A - Z is the number of neutrons in a nucleus. He should remember that isotopes are chemically similar atoms, having the same Z, but having a different A; and that isobars have the same A, but different Z's. Isomers are different energy states of a nucleus with a given A and Z. He should remember and understand the general features of nuclear force properties and the nuclear energy levels resulting from these forces.

b. The several succeeding sections will describe phenomena which are readily explained in terms of these nuclear energy levels and in the light of material presented here. Therefore, the student should be familiar with this information.

77. PROBLEMS

a. Using the periodic chart, figure 10 in paragraph 62, find all the isotopes of tin. Find natural isobars on the chart for at least six of the tin isotopes; e.g.,

$$_{50}Sn^{112}$$

has the isobar

$$_{48}Cd^{112}$$

b. Calculate the n/p ratio for Ca-40, Zr-92, Xe-131, and Pu-239.

SECTION II. PARTICLES

78. GENERAL

This section is intended to acquaint the student with the properties of the basic particles involved in nuclear physics. In addition to neutrons, protons, and electrons, combinations such as the deuteron, triton, alpha, and other particles of theoretical and experimental interest in the field of physics will be discussed. A description of the properties of three important elementary particles will be given first.

79. DESCRIPTION

a. The proton is the nucleus of a hydrogen ($_1H^1$) atom. It is a basic building block in all nuclei. It has a positive electric charge of +e, 4.80×10^{-10} esu; a mass of 1840 electron masses, 1.66×10^{-24} gm, or 1.00758 amu. It exerts nuclear forces on other nucleons. The symbol for a proton is $_1p^1$ or $_1H^1$, or simply p.

b. The neutron is electrically neutral and has a mass of about 1840 electron masses, 1.66×10^{-24} gm, or 1.00894 amu. It is a nucleon; it is basic in nuclear construction; and it exerts nuclear forces on other nucleons. The symbol of the neutron is $_0n^1$, or simply n.

c. The electron is the mobile negative charge in atoms, having an electric charge of -e, 4.80×10^{-10} esu, and a mass of 9×10^{-28} gm (or 0.00055 amu). It exists in the outer structure of atoms, not in the nucleus, and is largely responsible for interatomic and molecular forces. When an electron is ejected from a nucleus in radioactive processes, it is called a β^- particle. The symbols are:

$$_{-1}e^0,\ _{-1}\beta^0,\ \beta^-,$$

or simply e.

80. INTERACTION BETWEEN PARTICLES

a. These three elementary particles interact in several ways. Electrostatic forces exist between any two charges, according to the formula:

$$F = \frac{e_1 e_2}{r^2},$$

where e_1 and e_2 are the charges, and r is the separation. Therefore, protons exert electric forces on other protons and upon electrons.

b. Nuclear forces have already been described as having short range, being attractive but saturable, strong, charge independent, and spin dependent. These forces act between neutrons and protons and are roughly equal for (nn), (np), and (pp) combinations. The various properties of nuclear forces are partly accounted for by the meson theory, which will be mentioned later in this section.

c. The interactions of photons are manifold. Gamma rays of sufficient energy can create electron-positron pairs; that is, a gamma

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ray may cease to exist as such and give rise to an electron and a positron in its stead. This is the pair production process. In other cases, a photon may excite a nucleus to a higher state, or it may excite or ionize an atom. All these photon reactions are basically electromagnetic interactions; the electric and magnetic fields of the photon exerting forces on the electric and magnetic fields of the particles involved.

81. CHART OF ELEMENTARY PARTICLES

a. This section presents a chart of most of the particles presently considered to be elementary. The term elementary particle means one which is not composed of other particles. Although a particle may convert itself into others, it is not composed of these others until its conversion, but is considered to be a basic entity.

b. This chart lists various properties of the elementary particles: mass, charge, decay if any, how obtained, how discovered, and their role in physics. A discussion of some of these properties will be made later. In addition to the elementary particles, certain basic aggregates of elementary particles will be listed which are of use and importance in physics.

82. BEHAVIOR OF PARTICLES

a. In figure 24 (pages and), note that certain of these particles convert to others by radioactive decay. The free neutron decays to a proton, an electron (β particle) and a neutrino, with a half life of about 20 minutes. This may not be construed as implying that a neutron is composed of a proton, electron, and neutrino waiting to fly apart. A neutron bound into a nucleus will not in general decay. If it does so in certain circumstances, the nucleus is said to decay by β activity.

b. The positron is an interesting particle, demonstrated theoretically by Dirac's quantum mechanics in 1930, and found experimentally later. Dirac assumed that all space is pervaded by electrons in negative energy states, which are unobservable. An observable electron is in a positive energy state. Under some circumstances (e.g., under the influence of a high energy γ-ray) a negative energy electron may be kicked up into a positive energy state and observed as such. A "hole" in the negative energy state is then left, and this "hole" moves about as though it were a positive electron. Therefore, the positron's properties are nearly identical to those of the electron, except that it moves in the opposite direction in electric fields; that is, its charge is opposite.

c. When a positron meets an electron, it may combine, and the energy of the two electron masses is converted to electromagnetic radiation. On the Dirac picture, this annihilation process is a positive energy state electron making a transition to the negative energy hole, releasing energy. This transition requires the formation of two photons, in order to conserve spin in the process. The detailed theory is not necessary for the student now, and the further pertinent discussion of production of positron-electron pairs is given in paragraph 110.

d. The neutrino is another interesting particle whose existence was postulated on purely theoretical grounds. In the process of β decay of neutron and of nuclei, the energy of the β particle varies up to some definite maximum value. It was shown that the maximum value of energy was available in the nuclear transition which ejected the β particle, but that normally only a part of this energy was carried off by the β particle. Also, the spin angular momentum of the original nucleus differed by one-half unit from the sum of the spins of the resultant particles. These two discrepancies were explained by using an additional particle, the neutrino. The neutrino and β^- particle are emitted together. The neutrino had to have essentially no mass, no charge, but spin one half. Experiments performed to find any direct interaction of the neutrino have been so far unsuccessful, but this elusive particle is observed indirectly. β-active nuclei are observed to recoil with momenta which indicate the existence of the neutrino.

e. The alpha particle, deuteron, and triton are aggregates of protons and neutrons which tend to stick together during nuclear reactions. Thus α particles are emitted in heavy element radioactivity. Deuterons are emitted and absorbed in certain reactions. Tritons, or $_1H^3$ nuclei, are radioactive, and decay to $_2He^3$ with a 12-year half life. However, cosmic ray neutrons are continually forming tritium from deuterium, so that a minute amount exists in nature.

f. A gamma ray is included as an elementary particle because these photons behave like particles in their interactions. A theory similar to the meson theory has been used to describe the interaction of photons with matter, and to explain the electrostatic field forces. Under this theory, photons are exchanged between electric charges, and the electric forces result. Normally these photons are unobservable, unless energy is supplied to accelerate a charge, in which case observable radiation is emitted. These theories of exchange forces and electromagnetic field quantization need not be considered as important for this course, only as interesting supplementary information. Further reading along these lines for interested students might be had in Glasstone, Sourcebook on Atomic Energy, Sec. 12.75-12.82,

Particle & Symbol	Charge	Mass	Remarks on Discovery, How Obtained, Purpose
proton $_1p^1$	+e	1.00758 amu or 1840 me* or 1.67 x 10^{-24} g 931 Mev	Rutherford discovered proton by (α , p) reaction in nitrogen. Hydrogen nucleus. Basic charged nuclear particle.
neutron $_0n^1$	0	1.00894 amu or 1840 me or 1.67 x 10^{-24} g or 931 Mev	Chadwick discovered neutron by (α , n) reaction on beryllium. Basic neutral nuclear particle. Free neutron decays: $_0n^1 \rightarrow {}_1p^1 + {}_{-1}e^0 + {}_0\nu^0$ Half life 20 min.
electron $_{-1}e^0$ or β^-	-e	.00055 amu 1 me or 9.1 x 10^{-24} g	Electrons are the orbital structure in atoms; carriers of electricity.
positron $_{+1}e^0$ or β^+	+e	.00055 amu 1 me or 9.1 x 10^{-28} g	Anderson in 1933 discovered positron in cosmic rays. Predicted by Dirac theory of quantum mechanics of electron. Recombines with an electron, forming 2 γ's.
neutrino $_0\nu^0$	0	< 5 Kev	Carries off excess energy, momentum, and spin in β decay. Difficult to detect directly.

Particle & Symbol	Charge	Mass	Remarks on Discovery, How Obtained, Purpose
gamma ray $_0\gamma^0$	0	0	Electromagnetic field quanta, photons with $E = h\nu$.
alpha particle $_2\alpha^4$	+2e	4.0028 amu	Combination of 2p + 2n into a $_2He^4$ nucleus. A radioactive decay particle.
deuteron $_1d^2$	+e	2.01416 amu	An $_1H^2$ nucleus, used in many nuclear particle reactions.
triton $_1t^3$	+e	3.01647 amu	An $_1H^3$ nucleus, used in nuclear reactions. It decays with half life of 12 years. $_1H^3 \rightarrow {}_2He^3 + \beta^- + \nu$

*me = mass of electron

Figure 24. Table of Elementary Particles

and in Pollard and Davidson, Applied Nuclear Physics, Second Edition, chapter 12.

83. WAVE-PARTICLE DUALISM

a. One further concept regarding particles will be useful in thinking about nuclear physics. It has been mentioned that photons travel as electromagnetic waves but are absorbed and emitted as though they were particles. In other words, radiation may be regarded as having a dual wave-particle nature.

b. This dualism of the wave and particle functions of radiation led Louis de Broglie to suggest that a similar dualism might exist for material particles. He showed that a particle of mass m moving with a velocity v should be associated with waves of length λ, given by

$$\lambda = \frac{h}{mv} \text{ (h = Planck's constant)}$$

mv is the momentum of the particle, which is often represented by the symbol p.

c. Calculations show that for anything except the smallest particles, the wavelengths of the matter waves, as they are often called, are extremely small. No means is available at present to measure such wavelengths.

d. Experimental results with small particles showed de Broglie's assumption to be correct. A beam of electrons actually was diffracted by a diffracting screen exactly as if the electrons were photons. Thus, the wave-particle duality may be considered to be a fundamental property of nature.

e. In view of this property, one may wonder if there is any point in making a distinction between a wave and a particle. In a sense, such a distinction is meaningless, since everything has a wave character or a particle character, depending on the circumstances.

f. Particles or waves are generally so classified because of their familiar properties. Neutrons or molecules are referred to as particles because their familiar properties (mass, volume, etc.) are generally associated with particles. Light or gamma rays are referred to as waves because their familiar properties are generally associated with waves.

SECTION III. BINDING ENERGY

84. GENERAL

In this section, the principles of nuclear binding energy will be discussed. Because all presently known methods of obtaining nuclear energy depend upon changes in binding energies, this subject is basic to an understanding of all atomic energy devices. The concept, methods of calculating binding energy, and methods of utilizing it will be discussed. For the sake of completeness and interest, the methods of measuring and computing atomic masses are also given.

85. DEFINITION

Binding energy is that energy which must be supplied to a group of particles to free them of each other's forces. This means that for a nucleus, the total binding energy is the energy needed to separate all the nuclear particles. Whenever two particles are held together by forces of any kind, there is some binding energy. For example, an electron in the hydrogen ground state orbit requires 13.5 ev of energy to pull it entirely away from the proton. When an electron is pulled into its orbit from a long distance ($n = \infty$) to the ground state ($n = 1$), a 13.5-ev photon is emitted. The atomic system is more stable in its $n = 1$ state; and the excess energy possessed by the electron when it was outside must be eliminated, in this case, by electromagnetic radiation. The energy lost in forming a bound state of electron and nucleus is the binding energy; and if a 13.5-ev photon enters a hydrogen atom, it may free the electron from its bound state.

86. MASS DEFECT

a. The nucleus of an atom contains neutrons and protons which are bound together by much stronger forces than the electric forces holding electrons in the atom. This means that more energy must be provided to pull the nucleus apart; consequently, the binding energy of the nucleus is much greater than that of orbital electrons.

b. According to the conservation law of mass and energy, $E = mc^2$, whenever energy is created, mass is lost. Now if it takes work to separate the nucleons from a nucleus, then some energy must have been given up in the process of binding these nucleons together. This amount of energy created in the binding process must therefore result in a loss of mass in the nuclear system. The loss of mass, called mass defect, corresponds to the binding energy. If B. E. is the binding energy of a nuclear system, then the mass defect ΔM is given by the equation:

$$B.E. = (\Delta M)\, c^2.$$

87. CALCULATION OF BINDING ENERGY

a. To see how this binding energy concept enters into the nuclear picture given in paragraph 73, consider the process of forming a deuteron from a neutron and a proton. The mass of a proton is 1.00758 amu, and that of a neutron is 1.00894 amu. Thus, the total mass of the constituent particles of a deuteron is 2.01652 amu. The measured mass of the deuteron is 2.01416 amu, which is 0.00236 amu lighter than the sum of its parts. In other words,

$$M_p + M_n = M_d + \Delta M,$$

where M_p, M_n, and M_d are proton, neutron, and deuteron masses respectively, and ΔM is the mass defect. Converted to energy units, 0.00236 amu is 2.2 Mev (multiply by 931 Mev/amu), and this energy is the measured binding energy of the deuteron. If 2.2 Mev is supplied to a deuteron, the neutron and proton may be separated. In this same way, mass defects and binding energy may be calculated for all nuclei whose masses are known accurately enough.

b. In Appendix IV, Table of Atomic Masses, a fairly complete list of common isotopes is given, with the atomic mass of each as determined by experiment. Notice that the nuclear masses are not given, but the total atomic masses, including electrons. If the mass of a nucleus is desired, the mass of Z electrons at 0.00055 amu per electron is subtracted from the atomic mass. However, to calculate binding energies, it is not necessary to use the nuclear mass, since larger atoms may be considered to be made up of hydrogen atoms (${}_1H^1$) and neutrons. Then, the electrons are added to the nuclear particle masses on both sides of the equation for mass defect. For example, calculation of the binding energy of ${}_2He^4$ is made as follows: First add 2 hydrogen atom masses and 2 neutron masses. The hydrogen atom masses contain one electron mass each.

From the table,

$$M_1H^1 = 1.00813 \;:\; 2\ MH = 2.01626\ \text{amu}$$

$$Mn = 1.00894 \;:\; \underline{2\ Mn = 2.01788\ \text{amu}}$$

$$\text{Total } M = 4.03414\ \text{amu};$$

this figure includes two electron masses.

Also from the table, He-4 atomic mass = 4.00390. This figure also includes two electron masses. The nuclear mass in an He-4 atom is thus 4.00390 - 2 me and the nuclear mass of 2 protons and 2 neutrons is 4.03414 - 2 me. Therefore, the mass defect of $_2He^4$ nucleus is given by:

$$\Delta M = (4.03414 - 2) - (4.00390 - 2)$$

$$= (4.03414 - 4.00390) = 0.03024\ \text{amu}.$$

The student should clearly understand how he may calculate nuclear mass defects using the masses of neutral atoms as given in Appendix IV, Table of Atomic Masses. He should recognize that the electron masses balance out of the computation if neutral atomic masses are used throughout the problem. The total energy of the $_2He^4$ nucleus is then given by:

$$B.E. = \left(931\ \frac{\text{Mev}}{\text{amu}}\right)(0.03024\ \text{amu}) = 28.1\ \text{Mev}.$$

c. The student should calculate the binding energy of $_8O^{16}$ nuclei by the method described. For practice, calculate also the binding energy of $_6C^{14}$ and $_7N^{14}$ nuclei.

88. SIGMA

a. The total binding energy is the energy needed to totally disrupt the nucleus. A more useful concept for this course is that of binding energy per particle, Σ. This quantity is defined by:

$$\Sigma = \frac{\text{Total B.E.}}{A}\ \text{in Mev.}$$

Therefore, $$\Sigma = \frac{(\Delta M)\, c^2}{A}\ \text{in Mev}$$

$$= \frac{\Delta M}{A} \times 931,\ \text{where } \Delta M \text{ is in amu.}$$

Also, according to paragraph 87, the mass defect is:

$$\Delta M = \left[1.00813\ (Z) + 1.00894\ (A - Z)\right] - M_{atom}.$$

These equations are sufficient to calculate Σ from the isotopic atomic mass table.

b. The binding energy per particle is the average energy required to free a particle from the nucleus. It is also the apparent loss of energy due to the binding of one of the nucleons. Σ converted to mass is the apparent average loss of mass of a nucleon when it is bound into a nucleus. Thus,

$$\frac{\Sigma}{931} = \text{individual mass loss per nucleon.}$$

This can be said another way. When a proton or neutron is bound into a nucleus, it appears to have less mass than when it is free.

c. The Σ versus A curve plotted in figure 25 shows several significant features:

(1) The elements in the middle of the curve have the highest binding energy per particle, and therefore are the most stable.

(2) The largest binding energy per particle is about 8.7 Mev.

(3) Certain nuclei show extra stability as compared with their neighbors. This extra stability is evidenced by:

$${}_2He^4,\ {}_6C^{12},\ {}_8O^{16},\ {}_{14}Si^{28},\ \text{and}\ {}_{16}S^{32},$$

which are nuclei with alpha particle multiples.

(4) The change in binding energy per particle in a transmutation of a heavy nucleus into lighter nuclei is relatively small. The change in binding energy per particle in a transmutation involving fusing light nuclei into heavier is large.

89. FISSION AND FUSION

a. These last considerations show how the energy is released in the fission process and in the fusion process. When a nucleus fissions, it splits into two roughly equally sized smaller nuclei. The binding energy per particle increases in this process, and this change of energy is released as kinetic energy of the fission fragments. In

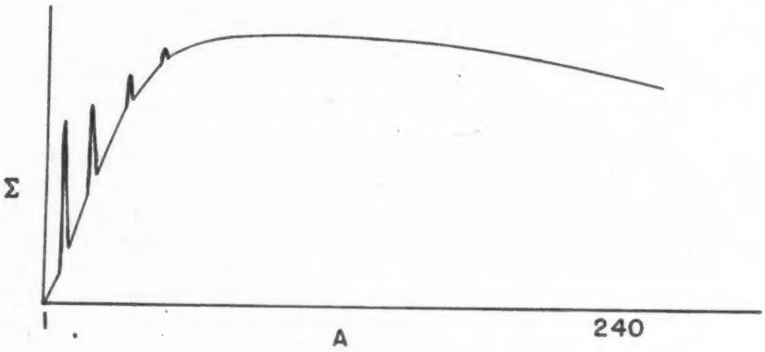

Figure 25. Σ Versus A Curve

other words, mass is lost in the fission process from the change in binding energy. No nucleons are destroyed, but their tighter binding releases energy. For example,

$$_{92}U^{235} \text{ has } \Sigma = 7.5 \text{ Mev/particle.}$$

It may fission into two middle range elements, with Σ about 8.3 Mev/particle. Thus 0.8 Mev/particle is released from the process of binding these nucleons more tightly. Including the neutron which caused fission, there are 236 particles; so the total energy released is (236) (0.8) = 189 Mev.

b. In a fusion reaction, several light nuclei, say $_1D^2$ and $_1T^3$ fuse together nuclearly to make a heavier, more tightly-bound nucleus. Thus again, the binding energy per particle increases, and this energy is released. The binding energy for $_1D^2$ is 2.2 Mev and for $_1T^3$ is 8.4 Mev. Under suitable conditions, $_1D^2$ and $_1T^3$ can be made to fuse into $_2He^4$ and an unbound neutron. The binding energy for $_2He^4$ is 28.2 Mev. Thus, the binding energy has increased 28.2 - (2.2 + 8.4) = 17.6 Mev per fusion.

90. CALCULATION OF ENERGY RELEASE

a. Another related approach to the release of energy in fission and fusion may be made. When nucleons bind together, energy is released. The amount of energy is the binding energy; and if this were supplied to the bound nucleus, it could separate it into its components. The way to calculate this binding energy for a given nucleus is to add the total constituent particle mass and compare it with the bound nucleus mass. The bound nucleus weighs less than the sum of its parts. This mass defect times c^2 equals the binding energy.

b. Now notice that each nucleon appears to have lost mass in being bound. The average loss of mass per nucleon times c^2 equals the binding energy per particle, Σ. Therefore, the most tightly-bound nuclei have nucleons whose average mass is least. Figure 26 plots a curve of average mass per nucleon. From this curve, one sees that per nucleon involved, the mass loss is greater for fusion than for fission. In both fission and fusion, the binding becomes tighter and the average mass for a particle in the nucleus decreases. This mass loss appears as a creation of energy. The average mass of a nucleon bound into a nucleus is given by the equation:

$$M_{av} = \frac{M}{A}$$

For U-235 $M_{av} = \frac{235.1133}{235} = 1.00048$

For Xe-132 $M_{av} = \frac{131.946}{132} = 0.99959$

For Mo-100, $M_{av} = \frac{99.945}{100} = 0.99945$

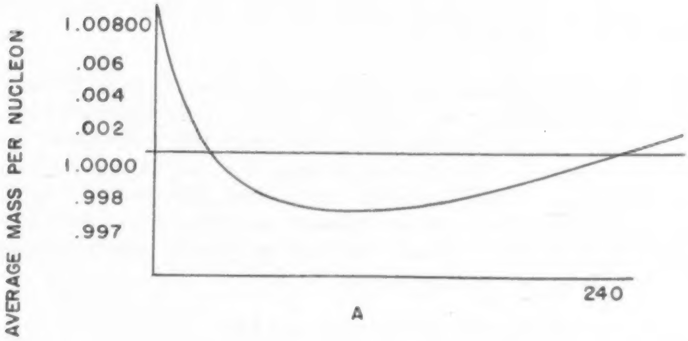

Figure 26. Average Mass Per Nucleon

Thus, in a hypothetical fission process where U-235 fissions to Xe-132 and Mo-100, the total energy released is equal to the total change in mass, which is equal to the sum of:

$$(100)\ (1.00048 - 0.99945)\ (931)$$

from conversion of 100 nucleons to a lower average mass and

$$(132)\ (1.00048 - 0.99959)\ (931)$$

from conversion of 132 nucleons to a lower average mass. The total energy released is thus:

$$(100)\ (931)\ (0.00103) + (132)\ (931)\ (0.00089) = 205 \text{ Mev}$$

for this particular fission.

c. The student should recognize that binding energy causes the apparent loss of mass of nuclear particles, and that the approaches made to binding energy release in fission and fusion in this paragraph and in paragraph 89 are really the same.

91. SUMMARY

From this chapter, the student should have learned what binding energy is and from what effect it arises. He should know the way in which energy is released in fission and fusion of nuclei, as well as what these processes are. He should be able to calculate total binding energies, Σ, mass defects, average bound nucleon mass, and the energy released in a given nuclear process where binding energy changes.

92. PROBLEMS

a. Calculate the total binding energy of the following nuclei:

(1) $_{6}C^{12}$

(2) $_{82}Pb^{207}$

(3) $_{92}U^{235}$

b. Calculate the binding energy per particle for each of the nuclei in problem a.

CHAPTER 5

RADIATION

SECTION I. RADIOACTIVITY

93. INTRODUCTION

Radioactivity is one of the more popular aspects of nuclear physics and is of rapidly growing importance in many fields. A knowledge of radioactivity is especially necessary for anyone working with atomic weapons. Some materials within these weapons are radioactive, as are the byproducts of an atomic explosion. An understanding of the effects of radioactivity on materials and humans is becoming vital to everyone in the atomic age.

94. HISTORY

Radioactivity was first discovered by Becquerel in 1896, quite by accident. He had intended to study the fluorescence of certain rocks after they were exposed to sunlight. Fortunately, the sun failed to shine in Paris for a few days, and the rocks, containing uranium, were left in a drawer beside the photographic plates. When developed, the plates showed a dark autoradiograph of the rocks. Evidently the rocks were emitting some kind of radiation of their own which was not dependent upon the sun. In 1898, Marie Curie named this process radioactivity.

95. CHARACTERISTICS OF NATURAL RADIOACTIVITY

a. Not long after Becquerel's discovery of the radioactivity of uranium, similar discoveries were made with a number of other heavy elements. Further experiments produced information about the nature of these mysterious radiations; the findings were startling at that time. The outstanding effects observed about radioactive elements include the following:

(1) There are three types of radiation emitted, and these differ greatly in their penetrating powers in various materials. See figure 27. These basic radiations are symbolized by three Greek

letters, alpha (α), beta (β), and gamma (γ).

(2) Any naturally radioactive element will emit one, or more, of these three basic radiations.

(3) The radiations are emitted continually and at a rate that is unaffected by temperature, pressure, or by the presence of other elements that may be chemically combined with a radioactive element.

(4) Radioactive elements are continually creating small quantities of other elements, some of which may also be radioactive. For example, radium generates helium and radon (both gases) as byproducts. Radon is also radioactive.

(5) Radioactive materials are constantly emitting energy and hence, are generally at higher temperatures than their surroundings. They are, therefore, sources of heat.

NOTE

Although these properties of radioactive elements seem peculiar at first, they become reasonable when more details have been given about the nature of radioactivity.

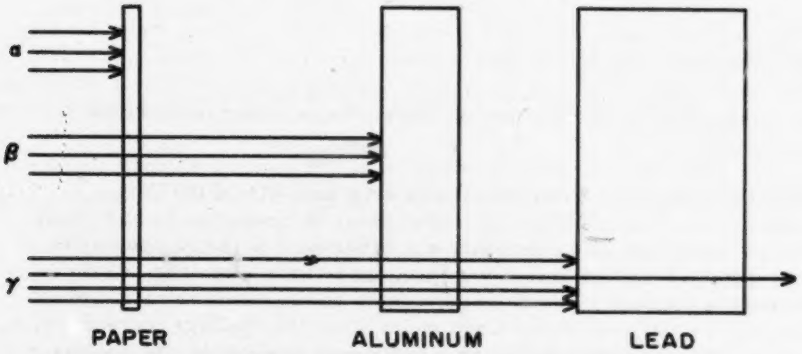

Figure 27. Demonstration of the Relative Penetrating Power of Three Nuclear Radiations

b. One of the most enlightening means of separating the three basic radiations is to pass a mixed beam of these radiations through a magnetic field. See figure 28. In doing this, the beam splits into three components. One component passes through the magnetic field without deflection, which indicates that it is uncharged. The other two components are deflected in opposite directions, indicating that one is positively charged and the other negatively charged. The positive radiation is called alpha (α), the negative radiation is called beta (β), and the neutral radiation is called gamma (γ).

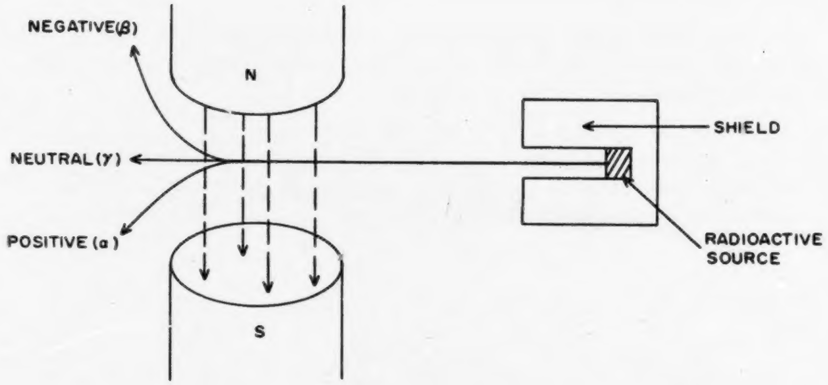

Figure 28. Deflection of Radiations in a Magnetic Field

c. The other unusual properties of radioactive elements arise primarily because these radiations originate within the nucleus. This explains why radioactivity is independent of temperature and other atoms that might be chemically combined with a radioactive atom. Temperature and chemical reactions have no appreciable effect upon an atom's nucleus.

d. The peculiar forces that are found to exist within a nucleus are such that many nuclei are unstable. Consequently they tend to change to a different form or structure in which they are more stable. The stability of a nucleus is closely related to the energy of the individual nucleons within the nucleus. The more energy possessed by the nucleons, the greater will be the chances that part of the nucleus will break off and escape, or that some arrangement will take place resulting in the emission of energy. In either case, the end product of radioactivity is a nucleus with less energy and therefore more stability.

e. When part of the structural material of a nucleus is emitted, the remaining material will form a new nucleus with either different Z, different A, or both. The main criterion for this to occur is that the nucleons of the "daughter" nucleus must have less energy than those of the "parent" nucleus. Finally, energy given up in the radioactive process heats up the source material and its container.

96. ALPHA DECAY

a. It has already been noted that alpha radiations are positively charged and have relatively short ranges. The nature of the alpha particle was determined by experimentation. Alpha particles from radon gas were collected in an evacuated bottle, and later analysis showed the contents of the bottle to be helium gas. Other experiments which measured the charge and mass of alpha particles supported this observation; as a result, alpha particles are known today to be helium-4 nuclei, composed of 2 protons and 2 neutrons (symbol $_2\alpha^4$).

b. Due to the large positive charge on an alpha particle (+2), it attracts electrons strongly. Alpha particles passing through a material tend to strip off electrons from atoms within the material. This process is called ionization, and atoms that have had electrons removed (or added) are called ions. The alpha particles are generally traveling fast enough so that the electrons stripped from surrounding matter are not captured by the alpha particle itself until it has slowed down considerably. The stripped electrons and positively charged particles remain on the path traced by alpha particles. Alphas are the most heavily ionizing radiation found in natural radioactivity and are capable of producing as many as 70,000 ion pairs in 1 centimeter of travel in air. An ion pair consists of 1 positively charged entity and 1 negatively charged entity. Upon slowing down and stopping, the alpha will gain two orbital electrons and become a stable $_2He^4$ atom. More details on ionization by alpha particles are given in section II.

c. One important characteristic of alphas is their discrete energies, which means that for any alpha-emitting material, emission takes place at only certain definite energies. In fact, many isotopes emit alphas of only one energy. For example, alphas from U-238 all have 4.2 Mev, while U-235 emits alphas with 4.39 and 4.56 Mev. The discrete alpha energies are in harmony with the observations that nuclei can exist only in certain allowed energy states. Therefore, any structural change should involve a discrete energy.

d. Since an alpha particle removes 2 protons and 2 neutrons from the parent material, the remaining structure forms a new nucleus with Z decreased by 2 and A decreased by 4. For example, $_{92}U^{238}$ decays by alpha emission to $_{90}Th^{234}$, and similarly $_{88}Ra^{226}$ decays to $_{86}Rn^{222}$.

e. Alpha decay has very important consequences in determining nuclear structure. Probably the best explanation of alpha decay is simply: as a nucleus gets more and more positively charged, a point is reached where the repulsive strength of the coulombic forces is comparable with the cohesive nuclear forces. This is found to occur in atoms whose atomic number is greater than 82. This actually oversimplifies alpha emission because calculations show that on the average an alpha group is bound to heavy atoms with an energy of about 25 Mev. However, alpha particles seldom have energies greater than 10 Mev, and it would seem that alpha emission should never occur. The diagram in figure 29 depicts a typical plot of the potential energy that an alpha particle would experience in the space inside and around a nucleus. As a positively charged particle approaches a nucleus, the repelling coulombic force increases sharply as designated by the curved slopes in figure 29. The greater the repelling force on the particle, the greater will be its potential energy. Once the positive particle gets within the nucleus, however, the repelling force ceases and the strong nuclear attraction takes over. This results in a sharp drop of about 25 Mev in the potential energy of the alpha particle. Considering, now, the reverse case, the strong nuclear attraction gives rise to a potential barrier for alpha emission, since an alpha should have 25 Mev in order to escape. However, the fact that alphas do escape with 4 to 10 Mev needs further explanation.

f. It should be no great surprise that ideas about nature, which are based on observations of samples of materials containing many atoms, do not apply exactly to the events taking place within a single atom. As a result, the classical notions of physics have been expanded greatly and incorporated into broader theories which have explained, in part, the peculiarities of atomic and nuclear physics. The theory upon which much of our understanding of the atom is based is called wave mechanics; when applied to alpha decay, it predicts that 4 to 10 Mev alpha particles can actually tunnel through the 25-Mev potential barrier set up by a nucleus (see paragraph 144). Although this barrier greatly reduces the rate at which alpha particles escape, their chances of escape are finite, and normal alpha decay results.

g. Another fact that is difficult to explain is why a nucleus does

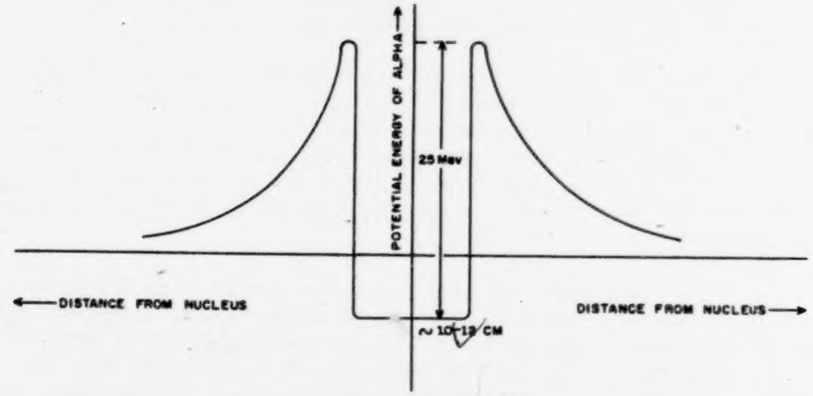

Figure 29. Plot of the Potential Energy of an Alpha With Range in the Vicinity of a Nucleus

not emit a proton alone, or a group of protons and neutrons larger than the alpha group. There is no really convincing argument to explain this except to say that it just happens this way. It develops that the energy needed to break up an alpha into its four constituent particles is 28.2 Mev, while the binding energy of a $_1H^3$ nucleus is only 8.4 Mev. Therefore, it would take 17.8 Mev to remove a proton from an alpha particle. This makes single proton emission very much less probable than alpha emission.

h. The nature of nuclear forces is such that an alpha particle and multiples of the alpha group (such as $_6C^{12}$ and $_8O^{16}$) are very stable structures. This does not exclude the possibility that a larger particle containing two or more alphas might be emitted. This practically never occurs because the huge potential barrier presented to a larger particle makes tunneling virtually impossible.

97. BETA DECAY

a. The reader will recall that beta radiation is characterized by a negative charge and a large charge-to-mass ratio (as compared to alphas). Further analysis shows that beta particles have the same charge and mass as electrons, and this has led to the definite identification of these particles as electrons. They are very special electrons, however, because they come from the nucleus and have very high energies. To distinguish them by source, they are called beta particles (symbol $_{-1}\beta^0$ or β^-) rather than electrons.

b. The emission of beta particles from a nucleus immediately brings up the following question: "How can electrons come from a nucleus made up of protons and neutrons, but no electrons?" Beta decay arises because under certain circumstances the nucleus can force a neutron to decompose into a proton and an electron. The outward symptom of these circumstances is an n/p ratio which lies above the stability region. See figure 23.

c. Since beta particles have a negative charge, they are able to ionize the atoms in the media through which they pass. However, due to the difference in charge and speed, the ionizing ability of beta particles is approximately one hundredth that of an alpha particle. In order to produce an ionizing event, a particle must give up enough energy to an atom to remove an electron. Therefore, the more ionizing a particle is, the faster it will give up its energy and the shorter will be its range. The beta particle travels faster than the alpha particle and has less charge; therefore, it cannot give up its energy as rapidly and that is why the range for beta particles is longer and the ionizing power less than for alpha particles.

d. A more striking difference between alpha and beta radioactivity is their emission energies. Recall that alpha particles are emitted with certain definite energies only. Beta particles, on the other hand, are emitted over a wide, continuous range of energies. This is demonstrated in figure 30, which shows a typical distribution of beta energies. The height of the curve at any energy level gives the percentage of beta particles which have this particular energy.

e. One important observation to be made from this curve is that no particles have an energy above that labeled E_{max}. It is also found that the energy difference between the nucleus before beta decay and the new nucleus after beta decay is equal to E_{max}. This actually is a very disturbing fact because it means that the great majority of beta particles, whose energy is less than E_{max}, have less energy than their parent nuclei gave up in emitting them. Here is a case where energy is apparently lost.

f. At first, it was thought that gamma rays might have been emitted in addition to the betas to account for the energy discrepancies. However, the gamma rays have never been detected. This has led scientists to make a bold postulate as to the existence of another

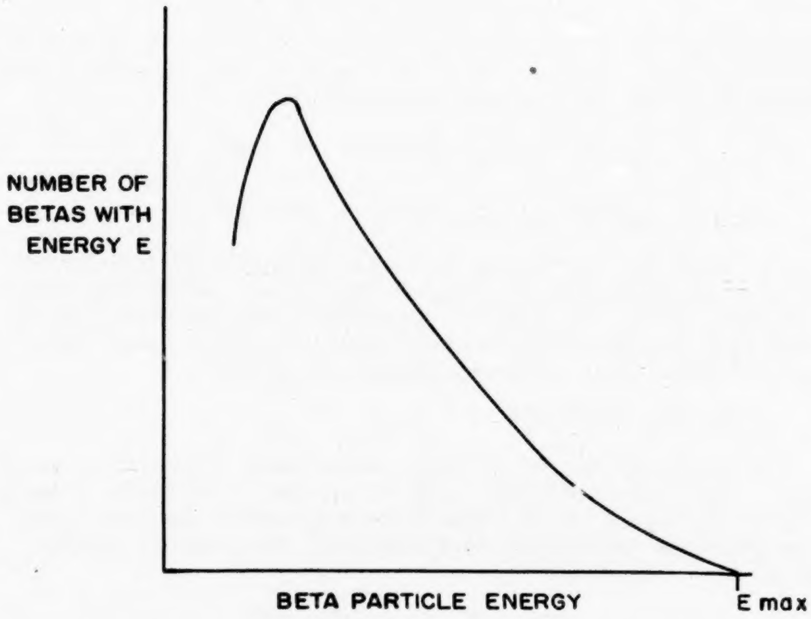

Figure 30. Energy Distribution (or Spectrum) of Beta Particles From Typical Source

particle called a neutrino (symbol ${}_0\eta^0$ pronounced eta). A neutrino is thought to be emitted in addition to a beta particle in such a way that the energy of the beta and the energy of the neutrino add up to E_{max}. Therefore, beta decay does not violate the idea that all subatomic changes involve discrete energies. The discrete energy in the case of beta decay is E_{max}.

g. Studies of beta decay have uncovered discrepancies other than energy that make the neutrino hypothesis seem even more necessary. However, the physical properties of the neutrino are such that it is extremely difficult to observe. This is because the neutrino is postulated to be a chargeless (Z = 0) particle with almost zero mass. Recent experiments indicate that the neutrino does, in fact, exist.

h. The complete reaction for beta decay is:

$$_0n^1 \longrightarrow {}_1P^1 + {}_{-1}\beta^0 + {}_0\eta^0$$

Note that beta decay changes the parent nucleus by increasing its Z by one (A remaining constant). The following are actual examples of beta emissions and the new elements which result:

$$_{90}Th^{234} \longrightarrow {}_{91}Pa^{234} + {}_{-1}\beta^0 + {}_0\eta^0$$

$$_{84}Po^{212} \longrightarrow {}_{85}At^{212} + {}_{-1}\beta^0 + {}_1\eta^0$$

i. Some beta emitters have several upper limit energies corresponding to different energy states of the parent, just as was found with alpha decay. For example, $_{90}Th^{234}$, mentioned above, emits betas with two upper limit energies, 0.20 Mev and 0.11 Mev, while $_{84}Po^{212}$ emits betas with a single E_{max} of 2.25 Mev.

98. ELECTRON CAPTURE

a. There are special instances where another type of decay takes place. This occurs primarily when the n/p ratio is below the stability region. See figure 23. A proton absorbs an atomic electron, a process called electron capture or K capture.[1] The complete reaction for electron capture is:

$$_1P^1 + {}_{-1}\beta^0 \longrightarrow {}_0n^1 + {}_0\eta^0$$

where the neutrino is again necessary to avoid conflicts with the law of energy conservation. Note that electron capture produces a new nucleus with Z increased by one.

b. Electron capture is always accompanied by the emission of X-rays, which results from another orbital electron falling into the place vacated by the captured electron. The energy lost by the electron is emitted as a photon whose frequency is in the X-ray range. However, the frequency of the photon is characteristic of an electron falling to the K shell of the product element rather than the original element.

99. POSITRON EMISSION

a. The same products as are produced by K shell capture are also produced by the emission of a particle called a positron, which has the mass of an electron, but a positive charge (symbol ${}_{+1}\beta^0$ or β^+). This reaction occurs when a proton is transformed by the influence of the nucleus into a positron and a neutron. The reaction is:

---

[1] Called K shell capture since the electron captured comes from the innermost orbital electron shell which is the K shell.

$$ {}_1p^1 \longrightarrow {}_0n^1 + {}_{+1}\beta^0 + {}_0\nu^0 $$

Note that this reaction does not occur in nature for free protons. The transformation occurs only under the influence of all the nucleons in the nucleus. A symptom which indicates that such a transformation might occur is that the n/p ratio is below the stable region. See figure 23. It should be mentioned that the reaction:

$$ {}_0n^1 \longrightarrow {}_1p^1 + {}_{-1}\beta^0 $$

does occur for free neutrons in addition to the transformation of neutrons inside the nucleus in β^- decay. The half life for free neutron decay is about 13 minutes. The transformations of the neutron and protons taking place in radioactivity are induced by forces present in the nucleus and under special conditions. Symptoms of these conditions are usually that the n/p ratios do not lie in the stability region.

b. Positron emission and K capture are relatively rare in natural radioactivity and are mentioned mainly for completeness. However, they do have interesting consequences to nuclear physics in general, and the curious reader is referred to advanced texts.

100. GAMMA RADIOACTIVITY

a. Gamma radiation is by far the most penetrating form of radioactivity and is different from alpha and beta radiations in that it is electromagnetic in nature. When a nucleus emits energy without a change in atomic mass or atomic number, the energy appears in the form of electromagnetic waves or photons. Since gamma photons are uncharged, they are unaffected by magnetic fields. Their ionizing ability is very much less than that of alpha or beta radiation, which explains their long range. Gamma rays do ionize by special processes which will be described in the next section.

b. The emission of gamma rays is accompanied by the change in energy state of the parent nucleus, and therefore gamma rays are always emitted with discrete energies. Frequently gamma rays are emitted in conjunction with beta or alpha particles. For example, in 94.3 percent of the atoms of ${}_{88}Ra^{226}$ decaying to ${}_{86}Rn^{222}$ by alpha emission, 4.79 Mev alpha particles occur alone. In the remaining 5.7 percent of the decays, 4.61-Mev alpha particles are followed by

0.18-Mev gamma rays. In nearly all polonium-210 alpha decays, however, 5.3-Mev alpha particles are emitted with no γ fission. In less than 0.001 percent of the cases, a 4.5-Mev alpha particle and an 0.8-Mev γ ray result. See figure 31.

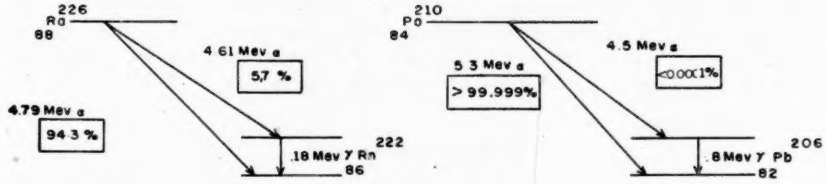

Figure 31. Energy Level Diagrams for Alpha Decay of Ra-226 and Po-210

101. NUCLEAR STABILITY AND RADIOACTIVITY

a. As previously noted, radioactivity is a result of the instability of nuclei. Because today's knowledge of nuclear forces is limited, science is unable to completely explain why some nuclei are more stable than others. However, certain rules have been observed to be followed by stable isotopes as to their relative numbers of neutrons and protons.

b. If the ratio of neutrons to protons is plotted against atomic number, a smooth curve results which lies close to the line representing a neutron to proton ratio of 1 and increases gradually to 1.6. See figure 23. This indicates that the forces between neutrons and protons are slightly stronger than those between neutrons alone or protons alone. These ideas fit with the previously noted facts about the stability of alpha particles and multiples of the alpha group, whose neutron-to-proton ratios are exactly one.

c. The gradual increase in the proportion of neutrons in going to heavier elements is attributed to the increasing coulombic repulsion from the protons in heavy nuclei. Were it not for the electrical charge of the protons, it is expected that all nuclei would have a neutron-to-proton ratio of nearly one. It is apparent, however, that additional neutrons are necessary for heavy nuclei to overcome coulombic repulsion. It is expected then that any nucleus whose neutron-to-proton ratio lies well off the stability curve will be radioactive and will emit a form of radiation that will place the product nucleus closer to the curve.

102. ARTIFICIAL RADIOACTIVITY

a. If stable nuclei on the curve in figure 23 are bombarded with external radiations of alpha and beta particles, protons, neutrons, etc., these particles are frequently captured and new isotopes (and elements) are produced. Many isotopes produced in this way have had their n/p ratio altered enough to become radioactive and are often capable of other forms of radioactivity than the alpha, beta, and gamma radiations emitted by natural radioactive isotopes. For example, alpha particles on $_{13}Al^{27}$ produce $_{15}P^{31}$ which decays rapidly to $_{15}P^{30}$ plus a neutron. Similarly, alpha particles on $_{7}N^{14}$ yield $_{8}O^{17}$ and a proton. This latter reaction is very interesting historically because it was the first man-controlled "transmutation" of one element into another. Since then, however, hundreds of other induced transmutations have been discovered.

b. If the n/p ratio is too large for stability, the most likely reactions are β^- decay or possibly neutron emission. If the n/p ratio is too small, however, β^+ decay, electron capture, or proton emission are possible.

103. DECAY LAWS

a. In paragraph 95, it was noted that no chemical or physical means could alter the rates at which a radioactive element decayed. Given a large sample of radioactive atoms, it is possible to predict how many atoms will decay in a given instant, but it is impossible to predict which atoms will decay. For this reason, radioactivity is called a random process.[1] The sample must consist of at least several millions of atoms or the argument that follows will not hold.

b. It is found that the number of atoms undergoing decay per second is proportional to the number of atoms present. Therefore, the ratio of the number of atoms decaying in a unit time to the total number of atoms present is a constant, called the decay constant, λ. λ can be interpreted as the probability that a given number of atoms will decay in a unit time and has units of time^{-1}. λ varies considerably from one material to another and can be found written with units varying from seconds^{-1} to years^{-1}.

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[1] A more familiar random process is encountered in flipping a coin. A large number of flips should produce 50 percent heads and 50 percent tails, but we are unable to predict which event will occur in a particular toss of the coin.

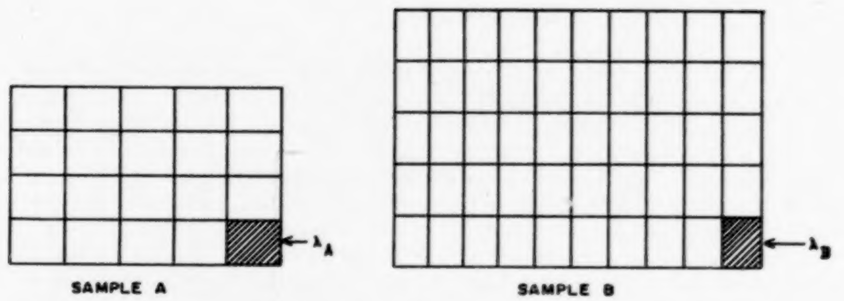


Figure 32. Example of the Significance of the Radioactive Decay Constant

NOTE

In sample A, one-twentieth of the sample decays in one unit time and, therefore, $\lambda_A = 0.05$. Sample B is less active, for $\lambda_B = 1/50 = 0.002$.

Rule I. If there are N atoms in a sample at some moment, and if λ expresses the fraction decaying in a unit time, Nλ is the number per unit time actually decaying at that moment.

c. For example, λ for U-238 is 1.51×10^{-10} yr^{-1}, and since 1 gram atomic weight of U-238 contains 6.02×10^{23} atoms (Avogadro's Number), there will be $(6.02 \times 10^{23})(1.51 \times 10^{-10})$ or 9×10^{13} decays per year in that much U-238.

d. The standard unit for measuring disintegration rate is the curie. One curie is defined as 3.7×10^{10} disintegrations per second. Since there are 3.1×10^{7} seconds in a year, the curie strength of one gaw of $_{92}U^{238}$ is:

$$\frac{9 \times 10^{13} \text{ dis/year}}{(3.1 \times 10^{7} \text{ sec/year})(3.7 \times 10^{10} \text{ dis/sec/curie})} = 10^{-4} \text{ curies}$$

e. To find the number of curies or the curie strength of a radioactive substance at any instant, we can use the following formula:

$$C = \frac{N\lambda}{3.7 \times 10^{10}}.$$

N is the number of radioactive atoms which are present at the time the curie strength is wanted. λ is the decay constant, but it must be expressed in seconds^{-1} since the constant 3.7×10^{10} is in disintegrations per second in the definition of a curie.

f. The definition of the curie was originally based on the radioactivity of 1 gram of $_{88}Ra^{226}$, for which λ is $1.38 \times 10^{-12}\ \text{sec}^{-1}$. One gram of this isotope is one two-hundred-and-twenty-sixth of a gaw and, therefore, contains:

$$1/226\ (6.03 \times 10^{23}) = 2.66 \times 10^{21} \text{ atoms.}$$

Its activity then is:

$$N\lambda = (2.66 \times 10^{21} \text{ atoms})\ (1.38 \times 10^{-12}\ \text{sec}^{-1})$$

$$= 3.71 \times 10^{10} \text{ disintegrations/sec}$$

$$= 1 \text{ curie.}$$

At present though, a curie is defined simply as 3.7×10^{10} disintegrations per second and is not defined in terms of a particular isotope.

g. A second useful fact about radioactive decay is the exponential decay law:

Rule II. If a sample originally contains No radioactive atoms, the number of atoms left after a time, t, is given by the formula:[1]

$$N = Noe^{-\lambda t}.$$

---

[1] This formula results from the original observation that the ratio of the number of atoms decaying in a unit time to the number present is a constant λ. Using the symbol Δ to indicate the "change in...", ΔN is read the change in N, Δt becomes the change in time, and the above statement can be written mathematically:

$$\frac{\Delta N}{\Delta t} = -\lambda N$$

This could be put in differential form as, $\frac{dN}{dt} = -\lambda N$ or $\frac{dN}{N} = -\lambda dt$.

Integrating from time $t = 0$, when there are No atoms, to time $t = t$, when there is the unknown number of atoms, N, left:

$$\int_{No}^{N} \frac{dN}{N} = -\lambda \int_{o}^{t} dt$$

$$\ln \frac{N}{No} = -\lambda t \quad \text{or} \quad N = Noe^{-\lambda t}.$$

h. One of the most useful characteristics of radioactivity is half life, which is the time for one-half of a sample of material to decay. This time is labeled $t_{1/2}$ and can be calculated from the above decay law. When one-half No atoms have decayed, N = No/2. Therefore:

$$\frac{No/2}{No} = \frac{1}{2} = e^{-\lambda t_{1/2}}$$

$$\ln 1/2 = -0.693 = -\lambda t_{1/2}$$

$$\text{Therefore, } t_{1/2} = \frac{0.693}{\lambda}.$$

i. Half life can be directly calculated from the decay constant and vice versa. Half life is more frequently quoted than the decay constant for a radioactive material. The usefulness of the radioactive decay law and half life are brought out by the following examples:

(1) The half life of ${}_{11}Na^{24}$ is 15 hours. If a sample of this isotope originally contains 48 grams, how many hours will be required to reduce this sample to 9 grams?

$$No = 48 \text{ grams}$$

$$N = 9 \text{ grams}$$

$$\lambda \text{ for } {}_{11}Na^{24} = 0.693/15 = 4.6 \times 10^{-2} \text{ hr}^{-1}.$$

Substitution in the decay law gives:

$$9 = 48e^{-4.6 \times 10^{-2}t}$$

$$\text{or, } \frac{3}{16} = e^{-4.6 \times 10^{-2}t}.$$

Note that N and No do not have to be converted explicitly into numbers of atoms per sample, providing that they are both expressed in units proportional to this quantity, such as grams or curies. Since 3/16 can be written as $e^{-1.68}$, this becomes:

$$e^{-1.68} = e^{-4.6 \times 10^{-2}t}$$

$$\text{or} \quad 1.68 = 4.6 \times 10^{-2}t$$

$$\text{and} \quad t = 36.5 \text{ hours}.$$

The concept of half life serves as a useful check for this solution since in 1 half life the sample is reduced to 24 grams; in 2 half lives, it is reduced to 12 grams; and therefore, it would take about 2-1/2 half lives to reduce it to 9 grams. The 2-1/2 half lives are 37.5 hours, which compares favorably with the calculated and correct value of 36.5 hours.

(2) The initial curie strength of a sample of Po-210 is 0.50 curies. Calculate the curie strength after 20 days using the ${}_{84}Po^{210}$ half life as 138.5 days.

$$\text{For } {}_{84}Po^{210},\ \lambda = 0.693/138.5 \text{ days} = 0.005 \text{ days}^{-1}$$

$$C = 0.50\, e^{-0.005\,(20)}$$

$$= 0.50\,(0.50) = 0.45 \text{ curies.}$$

j. The above calculations are often tedious and inconvenient and require the use of either a log log slide rule or a set of logarithms. Such calculations can be speeded up by use of a nomogram. See figure 33.

k. By placing a straightedge on the appropriate positions on the half life and time of decay scales, the fraction of radioactive material left or the fraction of radioactive material decayed can be read at the straightedge intersection with the scale on the right. They could also be used to give the relative curie strength remaining. Be sure to state half life and time of decay in the same units.

l. Example 1. For a radioisotope whose half life is 300 days (half-life scale) after 30 days (time scale) 0.068 (6.8 percent) will have decayed and 0.932 (93.2 percent) will remain (right-hand scale).

m. Example 2. If it is desired to let a radioisotope whose half life is 300 days decay to 64 percent of its original activity, it is necessary to wait 200 days (time scale).

104. RADIOACTIVE DECAY SERIES[1]

a. Naturally occurring radioactive nuclides, in general, decay into new nuclides which are also radioactive. The process continues until some stable, nonradioactive nuclide is formed. The process then halts. The intermediate nuclides form a radioactive decay series.

---

[1] The detailed decay chains for the four decay series are presented to improve student understanding of the general principles involved. No attempt should be made to memorize these detailed decay chains.

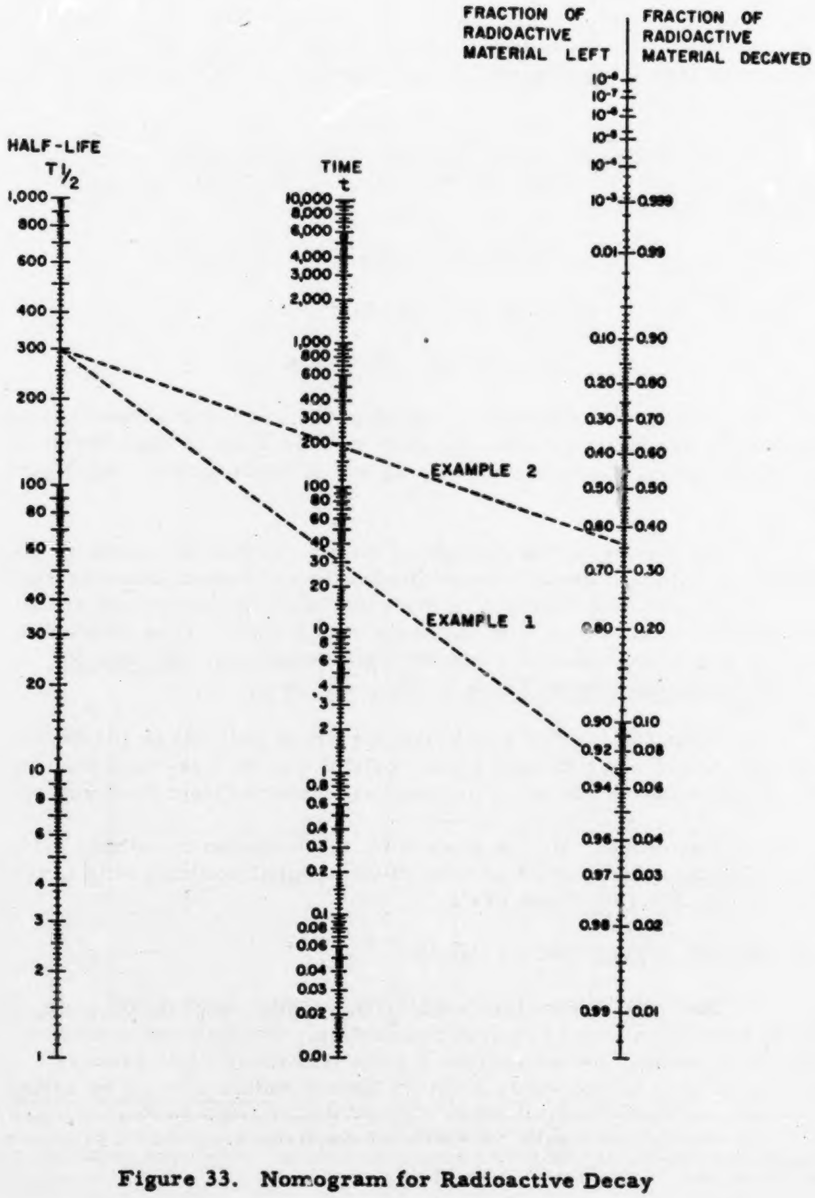


Figure 33. Nomogram for Radioactive Decay

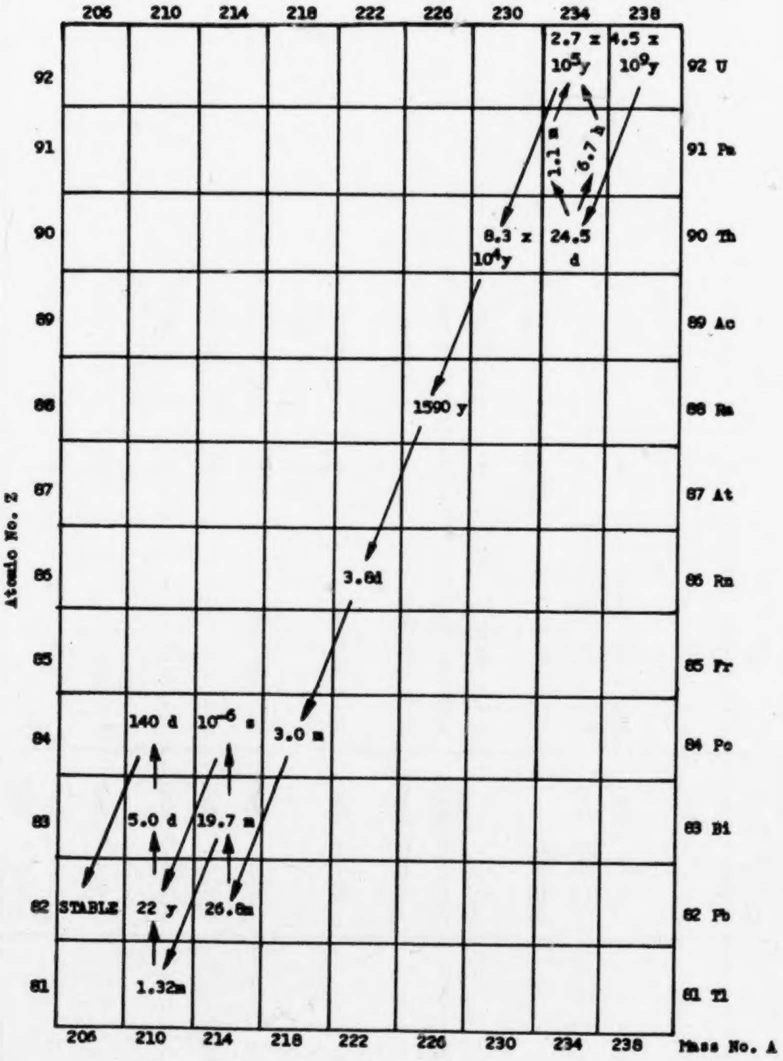


Figure 34. Uranium Decay Series (Half Lives Are Indicated for Each Step)

ELEMENT	SYMBOLS	HALF LIFE (T1/2)	TYPE OF EMISSION	RANGES OR ENERGY PARTICLE EMITTED: α IN CMS, β AND γ IN MEV.
Uranium	$_{92}U^{238}$ (UI)	4.4 x 10^9 years	α	2.67 cm.
Thorium	$_{90}Th^{234}$ (UX_1)	24.5 days	β^-	0.13 Mev.
Protactinium	$_{91}Pa^{234}$ (UX_2)	1.14 minutes	β^- γ	2.32 Mev. 0.80 Mev.
Uranium	$_{92}U^{234}$ (UII)	3.4 x 10^5 years	α	3.23 cm.
Thorium (Ionium)	$_{90}Th^{230}$ (Io)	8.3 x 10^4 years	α	3.2 cm.
Radium	$_{88}Ra^{226}$	1590 years	α γ	3.39 cm. 0.19 Mev.
Radon	$_{86}Rn^{222}$	3.825 days	α	4.08 cm.
Polonium	$_{84}Po^{218}$ (RaA)	3.05 minutes	α	4.69 cm.
Lead	$_{82}Pb^{214}$ (RaB)	26.8 minutes	β^- γ	0.65 Mev.
Bismuth	$_{83}Bi^{214}$ (RaC)	19.7 minutes	α β^- γ	4.1 cm. 3.15 Mev. 1.8 Mev.
Polonium	$_{84}Po^{214}$ (RaC")	10^{-6} seconds	α	6.95 cm.
Thallium	$_{81}Tl^{210}$ (RaC')	1.32 minutes	β^-	1.80 Mev.
Lead	$_{82}Pb^{210}$ (RaD)	22 years	β^- γ	0.0255 Mev. 0.047 Mev.
Bismuth	$_{83}Bi^{210}$ (RaE)	5.0 days	βγ	1.17 Mev.
Polonium	$_{84}Po^{210}$ (RaF)	140 days	α	3.87 cm.
Lead	$_{82}Pb^{206}$ (RaG)	Stable		

Figure 35. The Uranium Series

b. Naturally occurring heavy radioactive substances fall into three series, in which "parent" elements decay into "daughter" elements and the chain stops with a stable lead isotope. These are the thorium series, uranium series, and actinium series.

c. The thorium series starts with $_{90}Th^{232}$ (the element in the series with the longest half life, $t_{1/2} = 1.39 \times 10^{10}$ years) and works its way down to $_{82}Pb^{208}$.

$$\begin{tikzcd}
{_{90}Th^{232}} \arrow[r, "\alpha"'] & {_{88}Ra^{228}} \arrow[r, "\beta"'] & {_{89}Ac^{228}} \arrow[r, "\beta"'] & {_{90}Th^{228}} \arrow[r, "\alpha"'] & {_{88}Ra^{224}}
\end{tikzcd}$$

$$\begin{tikzcd}
{(_{88}Ra^{224})} \arrow[r, "\alpha"'] & {_{86}Rn^{220}} \arrow[r, "\alpha"'] & {_{84}Po^{216}} \arrow[r, "\alpha"'] \arrow[dr, "\beta"'] & {_{82}Pb^{212}} \arrow[r, "\beta"'] & {_{83}Bi^{212}} \\
 & & & {_{85}At^{216}} \arrow[ur, "\alpha"'] &
\end{tikzcd}$$

$$\begin{tikzcd}
{(_{83}Bi^{212})} \arrow[r, "\beta"'] \arrow[dr, "\alpha"'] & {_{84}Po^{212}} \arrow[r, "\alpha"'] & {_{82}Pb^{208}} \\
 & {_{81}Tl^{208}} \arrow[ur, "\beta"'] &
\end{tikzcd}$$

The half lives of these various atoms vary from 1.39×10^{10} years to 3×10^{-7} seconds. In general, an ore containing $_{90}Th^{232}$ will have various amounts of all the others in the series in equilibrium. This fact is useful in determining the ages of rocks. Notice that the atomic mass numbers of all thorium series atoms are divisible by 4. That is, the atomic mass numbers may be represented as the number 4n, where n is an integer from 52 to 58. For this reason, the thorium series is sometimes called the 4n series.

d. The uranium series starts with $_{92}U^{238}$, and decays to $_{82}Pb^{206}$. The half lives vary from 4.51×10^{9} years to 1.5×10^{-4} seconds. In each case in the uranium series, the atomic mass number may be represented by the number (4n + 2) where n is an integer ranging from 51 to 59. Therefore, the uranium series may be called the 4n + 2 series. Charts showing the uranium series decay scheme are given in figures 34 and 35. The complete sequence is:

$$\begin{tikzcd}
{}_{92}U^{238} \arrow[r, "\alpha"'] & {}_{90}Th^{234} \arrow[r, "\beta"'] & {}_{91}Pa^{234} \arrow[r, "\beta"'] & {}_{92}U^{234} \arrow[r, "\alpha"'] & {}_{90}Th^{230}
\end{tikzcd}$$

$$\begin{tikzcd}
({}_{90}Th^{230}) \arrow[r, "\alpha"'] & {}_{88}Ra^{226} \arrow[r, "\alpha"'] & {}_{86}Rn^{222}
\end{tikzcd}$$

$$\begin{tikzcd}
({}_{86}Rn^{222}) \arrow[r, "\alpha"'] & {}_{84}Po^{218} \arrow[r, "\alpha"'] \arrow[dr, "\beta"'] & {}_{82}Pb^{214} \arrow[r, "\beta"'] & {}_{83}Bi^{214} \\
 & & {}_{85}At^{218} \arrow[ur, "\alpha"'] &
\end{tikzcd}$$

$$\begin{tikzcd}
({}_{83}Bi^{214}) \arrow[r, "\beta"'] \arrow[dr, "\alpha"'] & {}_{84}Po^{214} \arrow[r, "\alpha"'] & {}_{82}Pb^{210} \arrow[r, "\beta"'] & {}_{83}Bi^{210} \\
 & {}_{81}Tl^{210} \arrow[ur, "\beta"'] & &
\end{tikzcd}$$

$$\begin{tikzcd}
({}_{83}Bi^{210}) \arrow[r, "\beta"'] \arrow[dr, "\alpha"'] & {}_{84}Po^{210} \arrow[r, "\alpha"'] & {}_{82}Pb^{206} \\
 & {}_{81}Tl^{206} \arrow[ur, "\beta"'] &
\end{tikzcd}$$

e. The actinium series (formerly called actino-uranium) starts with ${}_{92}U^{235}$ and ends with ${}_{82}Pb^{207}$.

$$\begin{tikzcd}
{}_{92}U^{235} \arrow[r, "\alpha"'] & {}_{90}Th^{231} \arrow[r, "\beta"'] & {}_{91}Pa^{231} \arrow[r, "\alpha"'] & {}_{89}Ac^{227}
\end{tikzcd}$$

$$\begin{tikzcd}
({}_{89}Ac^{227}) \arrow[r, "\beta"'] \arrow[dr, "\alpha"'] & {}_{90}Th^{227} \arrow[r, "\alpha"'] & {}_{88}Ra^{223} \arrow[r, "\alpha"'] & {}_{86}Rn^{219} \\
 & {}_{87}Fr^{223} \arrow[ur, "\beta"'] & &
\end{tikzcd}$$

$$\begin{tikzcd}
({}_{86}Rn^{219}) \arrow[r, "\alpha"'] & {}_{84}Po^{215} \arrow[r, "\alpha"'] \arrow[dr, "\beta"'] & {}_{82}Pb^{211} \arrow[r, "\beta"'] & {}_{83}Bi^{211} \\
 & & {}_{85}At^{215} \arrow[ur, "\alpha"'] &
\end{tikzcd}$$

$$\begin{tikzcd}
({}_{83}Bi^{211}) \arrow[r, "\beta"'] \arrow[dr, "\alpha"'] & {}_{84}Po^{211} \arrow[r, "\alpha"] & {}_{82}Pb^{207} \\
& {}_{81}Tl^{207} \arrow[ur, "\beta"'] &
\end{tikzcd}$$

The half lives vary from 7.1 x 10^8 years to 10^{-4} seconds. This series has atomic mass numbers which may be represented as $(4n + 3)$ where n is an integer from 51 to 58. Therefore, the actinum series may be called the 4n + 3 series.

f. In all of the preceding series, there have occurred instances in which a radio element decays in two ways, α or β. The two "daughter" products decay to the same next element in the series. These decay branches are shown with the most probable decay on the top, and the less likely branch on the bottom. The branching ratios are useful in the detailed study of radioactive nuclei.

g. The student should have noticed that the 4n + 1 series was missing. There may have been one early in the earth's history, but the longest half life in this series is 2.2 x 10^6 years, belonging to neptunium, ${}_{93}Np^{237}$. Thus, if this substance once existed naturally, it would be decayed now. Men have made neptunium and other transuranic elements, and this artifically induced series is now known. The neptunium series has the following sequence:

$${}_{94}Pu^{241} \xrightarrow[\beta]{} {}_{95}Am^{241} \xrightarrow[\alpha]{} {}_{93}Np^{237} \xrightarrow[\alpha]{} {}_{91}Pa^{233}$$

$$({}_{91}Pa^{233}) \xrightarrow[\beta]{} {}_{92}U^{233} \xrightarrow[\alpha]{} {}_{90}Th^{229} \xrightarrow[\alpha]{} {}_{88}Ra^{225}$$

$$({}_{88}Ra^{225}) \xrightarrow[\beta]{} {}_{89}Ac^{225} \xrightarrow[\alpha]{} {}_{87}Fr^{221} \xrightarrow[\alpha]{} {}_{85}At^{217}$$

$$\begin{tikzcd}
({}_{85}At^{217}) \arrow[r, "\alpha"'] & {}_{83}Bi^{213} \arrow[r, "\beta"'] \arrow[dr, "\alpha"'] & {}_{84}Po^{213} \arrow[r, "\alpha"] & {}_{82}Pb^{209} \\
& & {}_{81}Tl^{209} \arrow[ur, "\beta"'] &
\end{tikzcd}$$

$$({}_{82}Pb^{209}) \xrightarrow[\beta]{} {}_{83}Bi^{209}$$

105. PROBLEMS

a. If the n/p ratio is too high, what type of radioactivity is likely to be present?

b. Three milligrams of Po-210 is what number of curies of Po? If the half life of Po-210 is 138 days, how much time will elapse before there is one curie left?

c. What is the decay constant of radium, whose half life is 1590 years? How many grams are in a 6-mc radium source?

d. Pu-240 decays by α-emission to what isotope? This isotope is also α active, as is its "daughter." Starting with Pu-240 and knowing the sequence of radiations is α, α, α, β^-, β^-, α, and α, what isotope is derived?

SECTION II. INTERACTION OF RADIATION WITH MATTER

106. INTRODUCTION

Radiation is said to interact with a substance if it transfers some of its energy to that substance. Studies of these transfers of energy provide useful information about the nature of radiation. Therefore, knowledge of the mechanisms by which radiation interacts with matter is of great practical importance. Primarily, interactions afford a means of detection of radiations, but studies of the interaction of radiation with matter have also produced vital data about characteristic properties of matter itself.

107. IONIZATION

a. The reader is reminded that the diameter of an atom is about 10,000 times the diameter of its nucleus and, therefore, the volume associated with an atom is, for the most part, empty space. When radiation travels through matter, it is likely to pass through many atoms with no detectable interaction. Also, since the cloud of electrons takes up most of an atom's volume, interactions are most likely to occur with electrons.

b. Many electrons are bound to their atoms fairly loosely and, therefore, are easily freed by external sources of energy such as radiation. This process is called ionization, and the charged particles which result are called ions. In general, ions are atomic particles characterized by a net electrical charge. Since an ionizing event produces two ions, ionization is usually measured in terms of the number of ion pairs produced. An electron and a positively charged particle are therefore an ion pair.

c. The number of ion pairs produced by radiation in a unit length of travel (usually one centimeter) is called the specific ionization. Specific ionization for a given radiation varies from one material (in which the ionization takes place) to another; but, in general, the energy necessary for ionization decreases with increasing atomic number, Z.

108. ALPHA PARTICLE INTERACTION

a. The most highly ionizing radiation is the alpha particle whose ionizing ability is attributable to its double, positive charge and relatively large mass and small velocity. An alpha particle ionizes when its electric field pulls electrons out of the atoms that it passes. In this process, energy is transferred from the alpha particle to the atom; and on the average, an alpha particle loses about 35.5 ev of energy in forming one ion pair. It is found, however, that this amount of energy is several times larger than the energy necessary to simply remove an electron. For example, it takes only 13.6 ev to ionize a hydrogen atom. The explanation is that the extra energy lost by the alpha is given to the electron as kinetic energy. Therefore, in addition to being freed, an electron is set into motion when an ion pair is formed. Example: A 5-Mev alpha particle is stopped in 3 centimeters of air. Calculate the specific ionizations of this particle.

$$\text{Total ion pairs} = \frac{5 \times 10^{6}\ \text{ev}}{35.5\ \text{ev/ion pair}} = 1.41 \times 10^{5}\ \text{ion pairs}$$

$$\text{Specific ionization} = \frac{1.41 \times 10^{5}\ \text{ion pair}}{3\ \text{cm}} = 4.7 \times 10^{4}\ \text{ion pair/cm}$$

b. It is also possible for an alpha particle to lose energy without ionization. Frequently, electrons will only receive enough energy to jump to an excited energy state, without being freed. This result is more probable when alpha particles are moving rapidly. The faster an alpha particle moves, the smaller will be the time spent in the vicinity of a particular atom. Therefore, a fast alpha particle has less time in which to transfer energy to an electron to produce an ionizing event. As a result, the specific ionization of alpha particles decreases with energy as shown in figure 36.

c. Another interesting observation about alpha particles is shown in figure 37 where the intensity of alpha particles is plotted

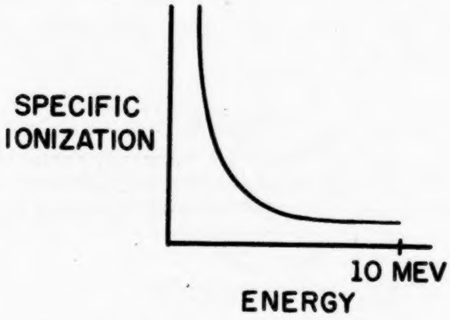


Figure 36. Specific Ionization Versus Energy for α Particles

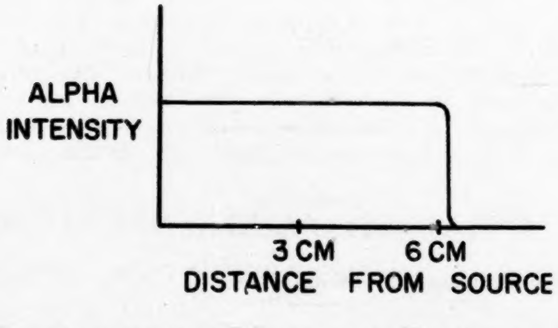


Figure 37. Alpha Intensity Versus Range

against distance from a source. This graph shows that all alpha particles from a given radioactive isotope have nearly the same range, which is attributed to the discrete energy levels in the radioactive nucleus. Because alpha particles from a given decay all have the same energy, they will all travel nearly the same distance in a given material. Slight differences in range among alpha particles of the same energy arise from the statistical nature of the ionizing events themselves.

d. For alpha particles of different energies, a variety of ranges result; but, in general, the maximum range of alpha particles is seldom over 8 centimeters in air. In a denser material, the range of alpha particles is considerably smaller, to the extent that they seldom are able to penetrate even tissue paper.

e. Figure 36 and figure 37 can be combined to produce a curve of specific ionization versus distance from a source. See figure 38. Note that as an alpha particle passes through a material, it is continually slowing down, which increases its ionizing ability. This accounts for the increase in specific ionization toward the end of the path of an alpha particle, as noted in figure 38.

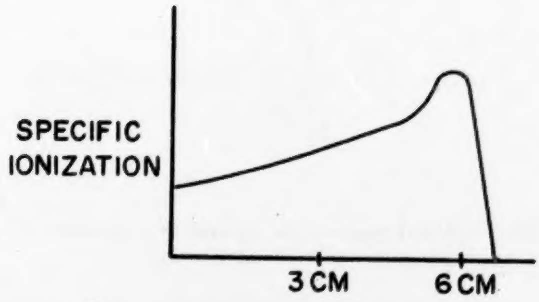


Figure 38. Specific Ionization Versus Range for α Particles

109. BETA PARTICLE INTERACTION

a. Beta particles, being charged electrically, are also capable of ionization in much the same manner that alpha particles ionize. However, the specific ionization is much smaller for beta particles (about one-hundredth that of alpha particles) because of their smaller mass and charge. With less mass, a beta particle travels much faster than an alpha with the same energy. To ionize an atom, a beta particle will have to come much closer to the atom than an alpha particle since its electric field is weaker and also less time is spent in the vicinity of any atom.

b. If specific ionization for beta particles is plotted against energy, a curve similar to that in figure 39 results. Note that for low

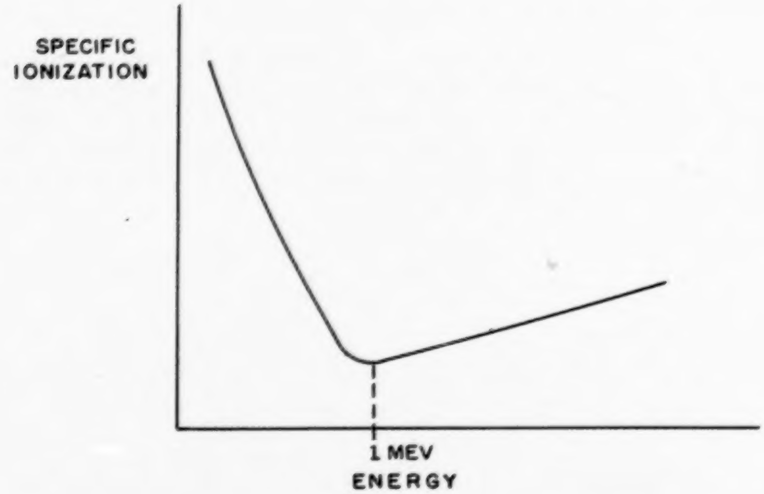


Figure 39. Typical Plot of the Specific Ionization of β Particles Versus Energy

energies, specific ionization falls off with increasing energy in a manner similar to that of alpha particles. It is found that, on the average, a beta particle loses about 32.5 ev in producing one ion pair in air.

c. The slight rise in specific ionization at high energies is not found with alpha particles. In the case of beta particles, it may be explained by a distortion of the electric and magnetic fields around a very rapidly moving charged particle (relativistic effects). The electric field about a slowly moving particle is symmetrical, as noted in figure 40. At very high velocities (near the velocity of light), the electric field becomes strengthened in the direction perpendicular to the direction of motion and causes the field of a rapidly moving particle to interact with atoms that would have been unaffected by a slower particle. See figure 41.

d. There is another means of interaction characteristic of high-speed beta particles. When a high-energy beta particle passes close to a heavy nucleus, it is deflected sharply by the strong electric field.

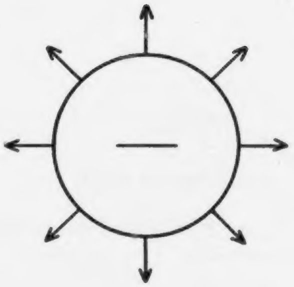


Figure 40. Electric Field Vectors for a Nonrelativistic Electron

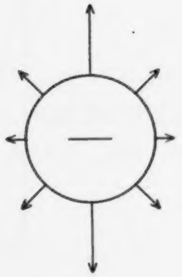


Figure 41. Electric Field Vectors for Relativistic Electron

In being deflected, a beta particle is found to emit energy in the form of an X-ray. Radiation produced in this way is called bremsstrahlung, which is a German word meaning "braking radiation." This term arises because a beta is continually slowed down by successive bremsstrahlung processes.

e. It should be noted that this process of deflecting charged particles to produce radiation does not apply to beta particles alone. Any moving charged particle will radiate when accelerated. However, beta particles are the only nuclear radiation light enough to be deflected (accelerated) to the extent that they will radiate X-rays. The energy of the radiated photons produced when slower particles are accelerated is usually insignificant.

f. Figure 42 shows how the two processes, ionization and bremsstrahlung, contribute to the rate of energy loss by beta particles at different energies. Note that bremsstrahlung is not significant below beta particle energies of about 1 Mev.

g. Beta particles of the same energy have a range which is nearly constant, just as was found in the case of alpha decays. However, if a plot is made of the number of beta particles with a given range versus range for the beta particles from a particular source, a curve resembling that in figure 43 results. As in the case of alpha emission, there is a definite upper limit to the range (R_{max}); but unlike alpha particles, the curve is not flat up to this range. See

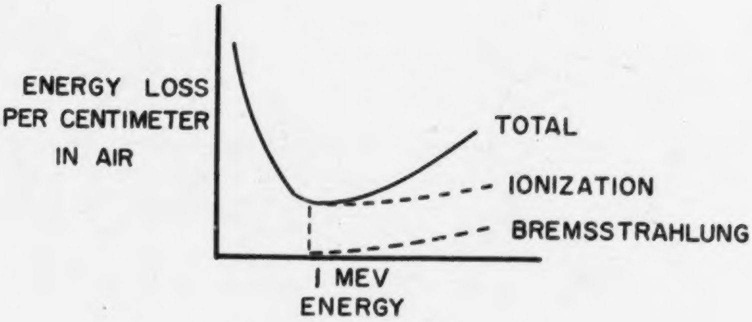


Figure 42. Energy Loss of β Particles

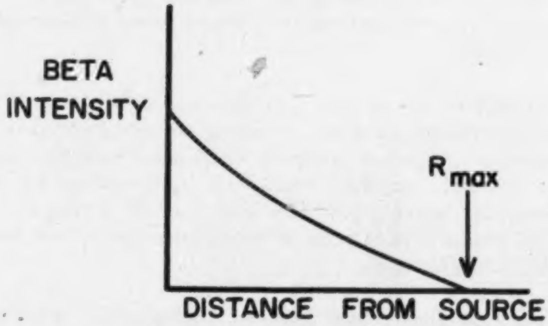


Figure 43. Beta Intensity Versus Range

figure 37. The continuous decrease in range of beta particles from a given beta emitter is accounted for by the fact that beta particles are not all emitted with the same energy, but rather with a distribution of energies similar to that shown in figure 30.

110 GAMMA RAY INTERACTION

a. Because gamma rays have zero charge and are electromagnetic in nature, it might be expected that gamma interaction with matter would be impossible. This is incorrect, however, because gamma rays are able to interact in three interesting ways: through the photoelectric effect, the Compton effect, and by pair production.

(1) Photoelectric Effect.

(a) Under certain conditions, a gamma ray photon can eject an electron from a metal by means of a collision in which an atom (really an electron of the atom) completely absorbs the energy of the photon. Therefore, the electron absorbs an amount of energy equal to $h\nu$ where ν is the frequency of the photon and h is Planck's constant. The photoelectric effect produces electrons whose kinetic energy is given by:

$$\text{Kinetic energy} = h\nu - W$$

where W is the amount of energy that the electron loses within the material in escaping.

(b) Photoelectric ionization by gamma rays is primarily a low-energy interaction and falls off rapidly with energy. See figure 44. In general, the probability of this type of interaction is greatest for low-frequency gammas and high-Z targets.

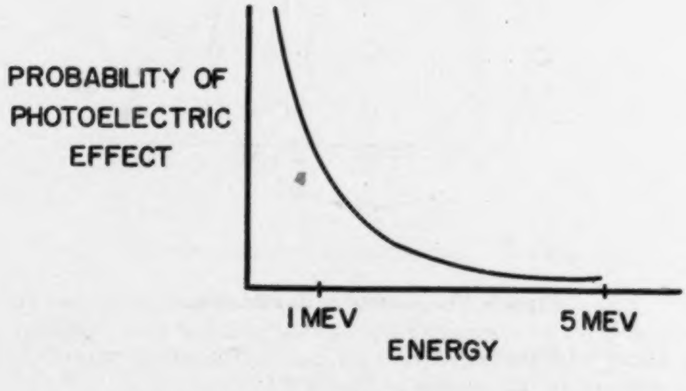


Figure 44. Typical Plot of the Dependence of the Photoelectric Effect Upon Energy

(2) Compton Effect.

(a) Frequently, the interaction of a photon with an electron results in only part of the photon's energy being absorbed. This process, called the Compton effect (or Compton scattering), serves as a second means of ionization for photons. A graphic description of the Compton effect appears in figure 45. One special feature of the Compton effect is the change in frequency of the scattered photon. Because the incident photon has given up some of its energy to the freed electron, the energy of the scattered photon will be less. However, the energy of photons is proportional to frequency ($E = h\nu$). Therefore, the scattered photon is found to have a new frequency which is lower than the original photon's frequency.

(b) The Compton effect extends to higher energies than the photoelectric effect but, like the latter, falls off with increasing energy. See figure 46. In general, the Compton effect is independent of atomic number of the absorbing medium.

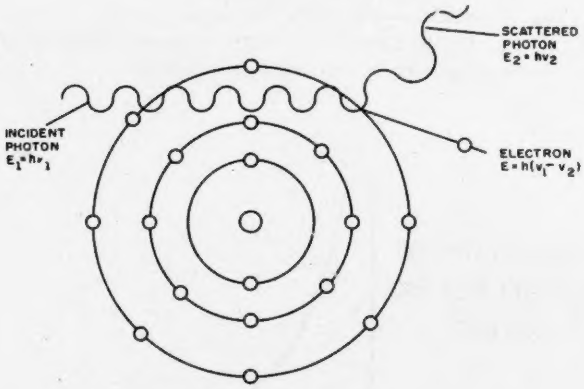


Figure 45. Compton Scattering

(3) Pair Production.

(a) When a high energy photon passes near a nucleus, it may be transformed into an electron and a positron (a positive electron). This process is simply a transfer of energy from the

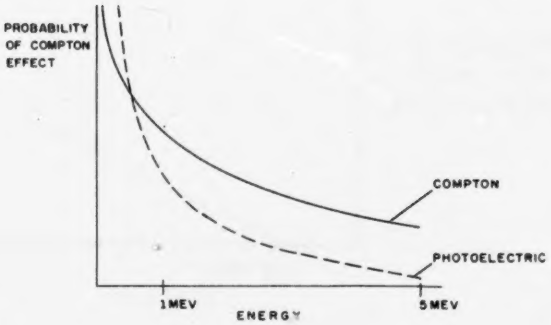


Figure 46. Variation of Compton Scattering With Energy of the Incident Gamma

electromagnetic form into mass, and therefore follows $E = Mc^2$. This brings up the question: "How much energy is necessary to create an electron and a positron?" Recall that 1 amu is equivalent to 931 Mev, and therefore:

$$2(0.00055)\,(931) = 1.02 \text{ Mev}$$

is the energy equivalent of 2 particles with mass of 0.00055 amu. It follows that 1.02 Mev is the minimum energy which a photon must possess in order to undergo pair production. Any excess energy over this threshold is given to the positron and electron as kinetic energy. It is not obvious why a third body, such as a nucleus, is necessary for pair production to take place. It is found, however, that energy cannot be converted into mass in the form of particles unless a third body is present to conserve momentum. Therefore, pair production does not take place in free space.

(b) A typical probability curve for pair production is shown in figure 47. Note that pair production increases with energy in contrast to the photoelectric and Compton processes.

(c) The creation of a positron and an electron by a photon is not the whole story of pair production, however, for positrons tend to combine with electrons, and in doing so become annihilated.

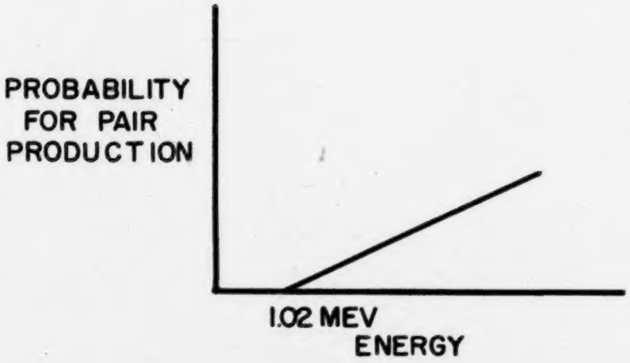


Figure 47. Dependence of Pair Production on Energy

The annihilation of positrons by electrons is an inverse pair production process, for here mass is converted into electromagnetic energy and two photons with energy 0.51 Mev are created and emitted in opposite directions. See figure 48.

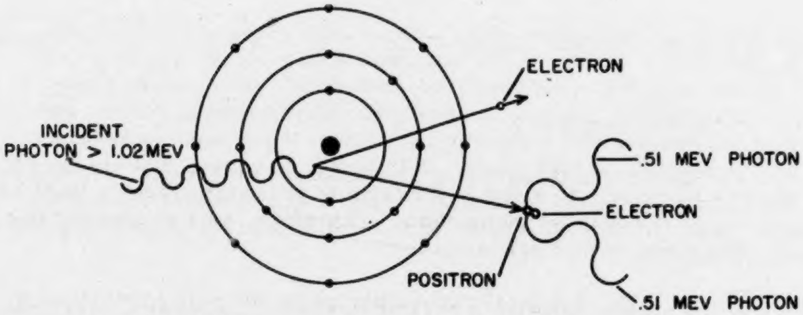

ELECTRON
INCIDENT PHOTON > 1.02 MEV
.51 MEV PHOTON
ELECTRON
POSITRON
.51 MEV PHOTON

Figure 48. Pair Production and Subsequent Positron Annihilation

b. The three means of interaction for gamma rays are summarized in figure 49, which shows the relative probability for each

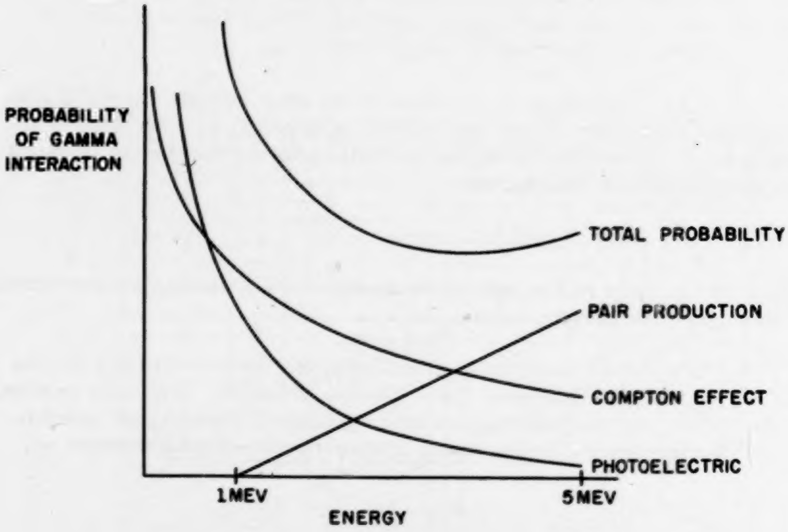


Figure 49. Interaction for Gamma Rays

reaction versus energy. The exact shape of this curve varies considerably from one material to another. In all cases, however, the curve is found to go through a definite minimum. This minimum is called the gamma ray window, because gamma rays of this energy pass through the material most easily. The position of the gamma window for lead is about 3 Mev, for iron about 7 Mev, and for aluminum about 20 Mev.

111. GAMMA ABSORPTION

a. Since the interaction of any radiation with matter results in a loss of energy by the radiation, this process is called absorption. Here, however, the discussion of absorption will be limited to gamma absorption only.

b. If a beam of gamma rays of intensity I_0 strikes a very thin slab of material of thickness x, the gamma intensity is reduced to I according to the relationship:

$$I = I_0 e^{-\mu x}$$

where μ is called the linear absorption coefficient and represents the fraction absorbed per unit length of travel. The letter x is the distance traveled expressed in the same units as μ.

c. It is interesting to calculate from this formula the thickness of material necessary to cut the radiation intensity by one-half. This is called the half thickness of the material and is referred to frequently in discussions of absorption.

$$\text{Half thickness} = \frac{0.693}{\mu}.$$

Figure 50 is a plot of the half thicknesses of different materials versus the energy of the gamma rays.

d. The linear absorption coefficient for most materials varies with the state of the material (gas, liquid, or solid). For this reason, the density, ρ, of the material is often included, forming an absorption coefficient known as the mass absorption coefficient defined as:

$$\nu_m = \frac{\nu}{\rho}.$$

This coefficient can be interpreted as the fraction of the gamma intensity which is absorbed in 1 gram of material through a surface area of 1 cm^2. The mass absorption coefficient, ν_m, has the advantage of being independent of the particular state of the absorbing material.

e. It is possible to use a nomogram to determine the relative fraction of gamma radiation that is transmitted through a given absorber. Such a nomogram is presented in figure 51 and is quite similar to the one used in chapter V for computing the fraction of material that has radioactively decayed.

f. In using the nomogram, one must be sure to use consistent units. Thus, both the half thickness and the thickness of absorbing material must have the same units.

g. Some typical examples are shown on figure 51. Thus, if we have 100 centimeters of a material whose half thickness if 20 centimeters for the gamma rays that are striking it, about 0.035 (3.5 percent) of the gamma rays will penetrate the material and 0.965 (96.5 percent) will be absorbed.

h. If the half thickness is 8 gms/cm^2; 1 gm/cm^2 of material would transmit about 91.6 percent of the gamma rays. These would be the units used if mass absorption coefficients were given.

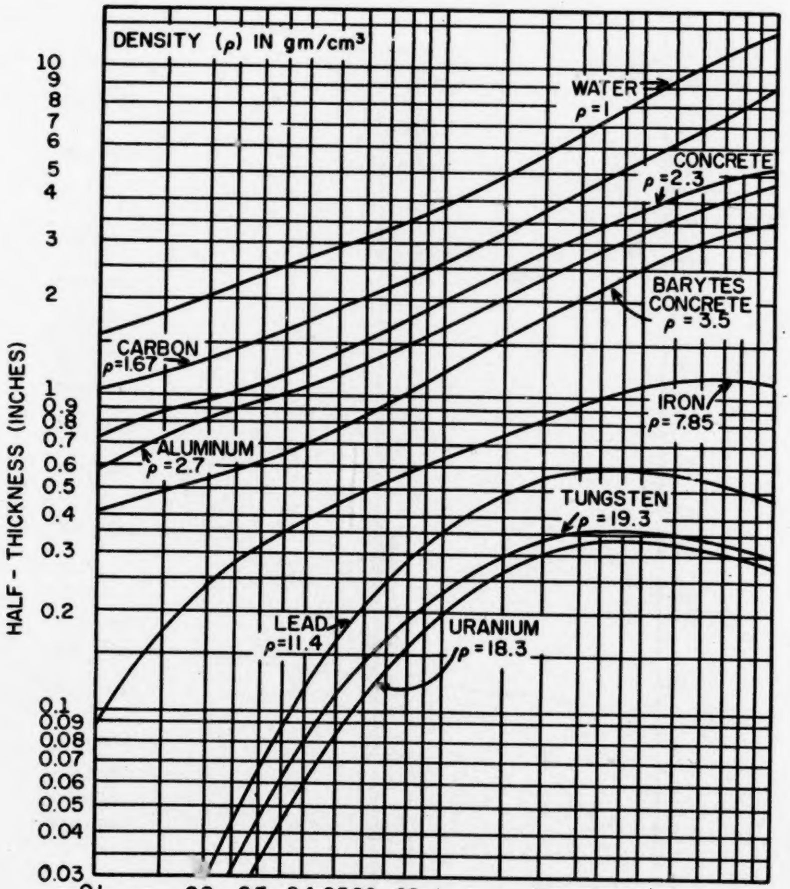


Figure 50. Half Thickness of Various Materials Versus Energy

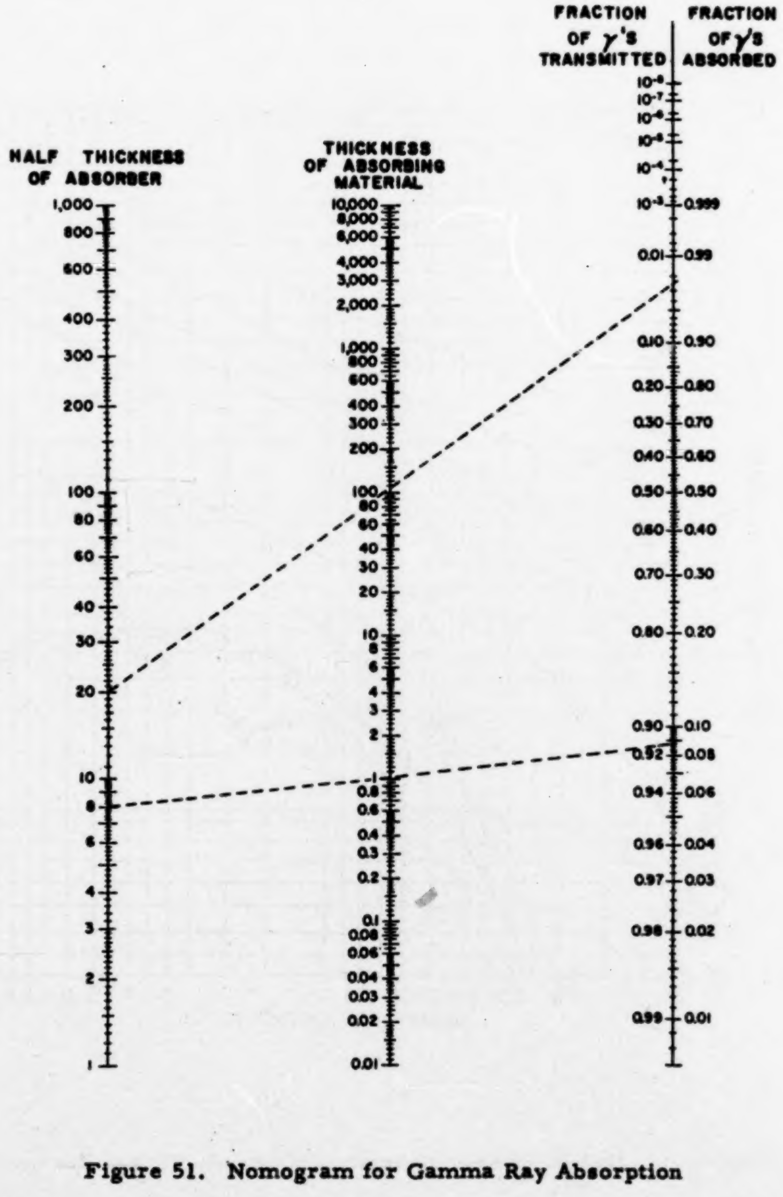


Figure 51. Nomogram for Gamma Ray Absorption

i. This nomogram also could be used to determine the half thickness of material if both the actual thickness of material and fraction of transmitted gammas were known. In all uses, the results will not strictly apply unless a very narrow beam of gamma rays is used.

j. This chapter has concentrated on the interactions of natural radiations with matter, and no mention has been made of other radiations such as neutrons, protons, etc. Neutron reactions are of sufficient importance to be left entirely for a later chapter. The reactions of other particles are partly included in the nuclear reactions chapter. Most of the techniques of atomic interaction of those particles involve the same principles outlined here for alpha, beta, and gamma radiations.

CHAPTER 6

NUCLEAR REACTIONS

SECTION I. GENERAL NUCLEAR REACTIONS

112. INTRODUCTION

Nuclear reactions are, as implied, reactions between two or more nuclei. They are to be distinguished from chemical reactions by two major respects. In a chemical reaction, none of the species involved have any change in their nuclei. The second major respect is a consideration of the energies involved in nuclear reactions. At most, the energies involved in chemical reactions are in the 0 to 10-ev region. Nuclear reactions involve energies of the order of millions of electron volts.

a. Particles Entering Into Nuclear Reactions

(1) Almost all the particles listed in figure 24 may be involved in nuclear reactions. In addition to the particles listed, two or more nuclei may be involved.

(2) In a nuclear reaction, normally one type of nuclear particle is ejected or pulled out of some source with a relatively high velocity as the bombarding or incident particle. The bombarding particle is then directed against nuclei which are normally at rest. These are called target nuclei. The products are the recoil nucleus (usually considered to be the largest product nucleus) and the ejected (smaller) particle or particles.

(3) Bombarding particles are usually neutrons, protons, deuterons, or alpha particles. The charged particles, except for the alpha particles, are usually accelerated in an electrostatic field. The alpha particle sources may be radioactive sources such as ${}_{84}Po^{210}$.

b. Force Fields Around Nuclei

(1) Neutrons, when used as bombarding particles, seem to have very little difficulty in penetrating into a target nucleus. Although

there is a positively charged electric field due to the protons already in the target nucleus, the neutron effectively does not "see" this electric field since it has no charge of its own. When the neutron comes within approximately 10^{-13} centimeters of the nucleus, it will be subject to the great cohesive (attractive) nuclear forces.

(2) For the proton, or any other positively charged particle, the above process does not hold. The proton, for example, will encounter a positively charged force field due to the protons in the nucleus. Since the proton is positively charged, the force field is repulsive in nature. The repulsive field increases very rapidly until the proton gets to about 10^{-13} centimeters from the nucleus. The cohesive attractive forces start acting at this distance and overcome the repulsive forces. The proton may then enter the nucleus. The effect is as if there were a "wall" that the proton must penetrate. This "wall" is called a barrier. The barrier ends approximately 10^{-12} centimeters from the center of the nucleus. See paragraph 96.

113. TYPES OF NUCLEAR REACTIONS

A nuclear reaction is said to occur whenever an incident particle enters a nuclear field; that is, when it enters the nucleus. Figures 52 to 56 are schematics of five basic nuclear reactions which can occur.

a. Elastic Scatter. One of the simplest nuclear reactions is the case of elastic scattering or elastic collision. This type of reaction is very similar to the collision of billiard balls. The conservation of momentum holds for the collision. No energy is transferred into exciting either the bombarding particle or the target nuclei. Physically, the bombarding particle may touch the target nucleus and bounce off; it may only come near the target nucleus and be deflected; or, it may hit the target quite hard, but still bounce off. The criterion is that no energy be transferred into nuclear excitation, although there usually is a transfer of kinetic energy. As long as this holds, the collision is elastic. Recall that the bombarding particle and the ejected particles are the same, and that the recoil and target nuclei are the same.

b. Inelastic Scatter. This is a collision process in which energy is transferred from the collision into nuclear excitations. A good analogy is the collision between soft rubber balls. Physically, the bombarding particle may enter the target nucleus, or only touch it. However, energy is transferred to the target nucleus and excites it to an energy level which is above the ground state. When the excited target nucleus returns to the ground state, it gives up this excitation energy in the form of electromagnetic radiation. This electromagnetic

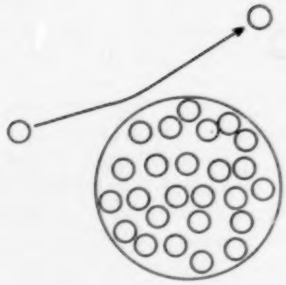


Figure 52. Elastic Scatter

radiation is gamma radiation. Thus, inelastic scatter is accompanied by gamma emission. Again, the bombarding and ejected particles are the same, and the target and recoil nuclei are the same.

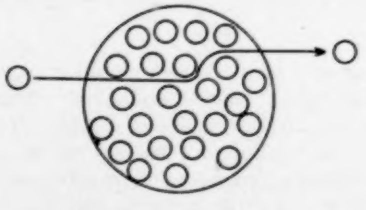


Figure 53. Inelastic Scatter

c. **Capture Reactions.** Capture reactions usually involve bombardment by neutrons. However, this is not always the case, as some capture reactions are known to occur in which other particles are used for bombardment. In the case of a capture, the bombarding particle enters the target nucleus and remains. When it does so, however, it also excites the new recoil nucleus to an energy level above the ground state. When the recoil nucleus returns to the ground state, it releases the excitation energy in the form of gamma radiation. Hence, capture is accompanied by gamma emission. The recoil nucleus is different in nature from the target nucleus, and there is no ejected particle.

d. **Particle Ejection on Bombardment.** In this case the incident particle enters the target nucleus. The energy imparted to the newly

formed nucleus is enough to eject another particle from the nucleus. The recoil nucleus is usually left in an excited condition and returns to the ground state with the emission of gamma radiation.

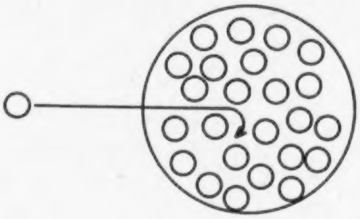


Figure 54. Capture

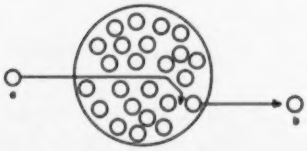


Figure 55. Particle Ejection on Bombardment

e. Fission. For fission reactions, a heavy nucleus is bombarded by some particle. Two large sized nuclei result, and several neutrons are emitted. The two recoil nuclei are called fission fragments. The fission fragments may be in an excited state. Actually, one can consider this class of reactions as a subclass of particle ejection on bombardment.

114. NOMENCLATURE FOR NUCLEAR REACTIONS

a. The general equation for a nuclear reaction may be written in the following manner:

$$_{Z1}a^{A1} + {}_{Z2}X^{AZ} \longrightarrow {}_{Z3}b^{A3} + {}_{Z4}Y^{A4} + Q.$$

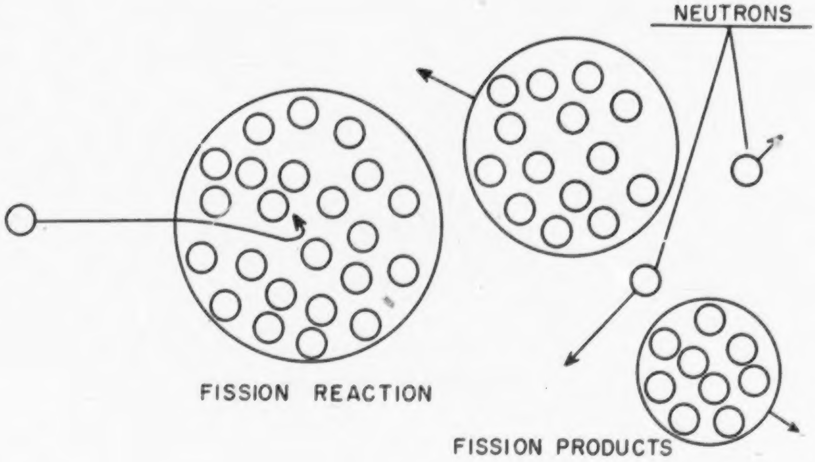


Figure 56. Fission

b. The symbol $_{Z}W^{A}$ has the accepted connotation. $_{Z1}a^{A1}$ is the bombarding or incident particle. For most reactions, it is a relatively light particle. Usual bombarding particles are: $_{0}n^{1}$, $_{1}H^{1}$, $_{1}H^{2}$, $_{1}H^{3}$, and $_{2}He^{4}$, although others may be used. $_{Z2}X^{A2}$ is the target nucleus. This at times may be called the parent nucleus.

$$_{Z1}a^{A1} + _{Z2}X^{A2}$$

are called the reactants or the incoming mass. $_{Z3}b^{A3}$ is the ejected particle. It is usually a light particle. $_{Z4}Y^{A4}$ is the recoil nucleus. It is also called the daughter nucleus. The sum $_{Z3}b^{A3} + _{Z4}Y^{A4}$ are the products or the outgoing mass.

c. The term, Q, on the right in the general equation is the mass balance or energy term.

115. RULES FOR NUCLEAR REACTIONS

a. There are a few rules which hold for nuclear reactions which shall be discussed before going into any specific reactions.

(1) Conservation of Nucleons. In a nuclear reaction, there is a conservation of the total number of nucleons. In the reaction,

$$_{Z1}a^{A1} + {}_{Z2}X^{A2} \longrightarrow {}_{Z3}b^{A3} + {}_{Z4}Y^{A4},$$

this means that A1 + A2 = A3 + A4. It does not mean that the total mass on each side of the equation is the same.

(2) Conservation of Nuclear Charge. Just as the number of nucleons is conserved, so also is the total nuclear charge. This holds also for nuclear reactions in which positrons and beta particles are involved. The reactions involve only the nucleus and not the orbital electrons. Thus, orbital electrons are not counted as nuclear charge. This conservation statement can be written as: Z1 + Z2 = Z3 + Z4. Any nuclear reaction which can be written having both A1 + A2 = A3 + A4 and Z1 + Z2 = Z3 + Z4 should be considered as a possibility.

(3) Conservation of Mass and Energy. The total mass is not conserved in a nuclear reaction. However, there is a conservation of the total of mass and energy. If the mass of the reactants is greater than the mass of the products, then energy must be released if the conservation of mass and energy is to hold. In the other case, where the mass of the products is greater than the mass of the reactants, then energy must be introduced to make the reaction go. The energy balance, or the mass difference, is taken into account by the Q term.

b. Example Reactions. The rules of nuclear reactions can be illustrated by considering a number of reactions of interest. The reaction,

$$_0n^1 + {}_6C^{12} \longrightarrow {}_0n^1 + {}_6C^{12},$$

is an important case of elastic scatter which is used to slow neutrons. Graphite is used as a moderator.

$$_0n^1 + {}_{48}Cd^{112} \longrightarrow {}_{48}Cd^{113}$$

is a reaction used to capture neutrons.

$$_2He^4 + {}_4Be^9 \longrightarrow {}_0n^1 + {}_6C^{12}$$

is used as a neutron source.

$$_0n^1 + {}_{92}U^{235} \longrightarrow {}_Zf1^A + {}_Zf2^A + (2 \text{ to } 3)\ {}_0n^1$$

is the well-known fission reaction. Radioactive decays may also be written as nuclear reactions.

$$_1H^3 \longrightarrow {}_{-1}\beta^0 + {}_2He^3$$

$$_{84}Po^{210} \longrightarrow {}_2\alpha^4 + {}_{82}Pb^{206}$$

$$_7N^{13} \longrightarrow {}_6C^{13} + {}_{+1}\beta^0$$

In all of these examples note that there is conservation of nucleons and conservation of nuclear charge. In addition, Q could be put on the right-hand side of each equation.

116. MECHANISM FOR REACTION

a. Nuclear reactions can be understood much more clearly if we adopt the concept of a compound nucleus. The compound nucleus is an intermediate state which is postulated to provide an understandable path along which a nuclear reaction can proceed. When all the details of a reaction are known, the reaction mechanism is said to be known.

b. The compound nucleus is an unstable intermediate in a nuclear reaction. The evidence for the existence of the compound nucleus is fairly conclusive except for the case of elastic scattering. The formation of the compound nucleus may be written as:

$$_{Z1}a^{A1} + {}_{Z2}X^{A2} \longrightarrow {}_{(Z1+Z2)}W^{(A1+A2)}$$ [1]

The compound nucleus is written as that nuclide which has an atomic number, that is the sum of the atomic numbers of the reactants. The total number of nucleons is also the sum of the nucleons of the reactants. The compound nucleus will usually be in an excited state. Note that compound nucleus can be formed any number of ways. For example, the formation of ($_5B^{11}$) can be had from:

NOTE
There is conservation of Z and A.

---

[1] The parentheses indicates an excited nuclear state.

$$_0n^1 + {}_5B^{10} \longrightarrow ({}_5B^{11})$$

$$_1H^2 + {}_4Be^9 \longrightarrow ({}_5B^{11})$$

$$_2He^4 + {}_3Li^7 \longrightarrow ({}_5B^{11}).$$

Therefore, the intermediate is independent of its formation to a great extent, the restrictions only being the conservation of Z and A. There is a good reason for this independence of formation of the compound nucleus. The half life of the compound nucleus is about 10^{-12} to 10^{-14} seconds. This time is much greater than the time required for a bombarding particle to traverse a target nucleus (assuming it is not slowed down very much in the process). Thus, the compound nucleus is not just that intermediate whose lifetime is the average length of time of a collision process. Let us calculate this collision or transit time. If one assumes a velocity of approximately 10^9 cm/sec for the bombarding particle and a typical target nucleus of diameter 10^{-12} centimeters, the time required to traverse the target is about 10^{-21} seconds. The compound nucleus lasts about 10^8 times longer than this. Essentially, then, the compound nucleus "forgot" how it was formed, although the energy level to which it is excited may vary with the reactants.

c. The breakup of the compound nucleus is dependent on the energy of the system. The possibilities for breakup can be easily listed. The only requirement is that of conservation of atomic number and the number of nucleons. For example, $({}_5B^{11})$ can decay into:

$$({}_5B^{11}) \begin{cases} \longrightarrow {}_2He^4 + {}_3Li^7 + Q^1 \\ \longrightarrow {}_4Be^{10} + {}_1H^1 + Q^2 \\ \longrightarrow {}_0n^1 + {}_5B^{10} + Q^3 \end{cases}$$

Note that in each case there is a conservation of Z and A. We have not, as yet, considered which of these breakup possibilities is the most probable. There are a total of nine possible reactions using $({}_5B^{11})$ as a compound nucleus. The possibilities are:

$$_0n^1 + {}_5B^{10} \longrightarrow ({}_5B^{11}) \longrightarrow {}_2He^4 + {}_3Li^7 + Q$$

$${}_1H^2 + {}_4Be^9 \longrightarrow ({}_5B^{11}) \longrightarrow {}_4Be^{10} + {}_1H^1 + Q$$

$${}_2He^4 + {}_3Li^7 \longrightarrow ({}_5B^{11}) \longrightarrow {}_0n^1 + {}_5B^{10} + Q.$$

Reactions such as ${}_0n^1 + {}_5B^{10} \longrightarrow {}_0n^1 + {}_5B^{10}$ can be elastic or inelastic collisions.

117. SIGNIFICANCE OF Q

a. The probability of a reaction occurring is tied up with the energy balance or mass balance term, Q. Let us look again at the general equation,

$${}_{Z1}a^{A1} + {}_{Z2}X^{A2} \longrightarrow {}_{Z3}b^{A3} + {}_{Z4}Y^{A4} + Q$$

The term Q is formally equivalent to a mass term. This is exactly the case. The energy balance term is the mass equivalent that is gained or lost in the reaction. The equation, as written, represents a nuclear reaction. Therefore, Q may be calculated from a mass balance of the equation. The mass equivalent of Q is:

$$Q = \text{Mass of reactants} - \text{Mass of products}.$$

If the reaction masses are in atomic mass units, the conversion to energy in Mev is:

$$Q\ (\text{Energy}) = (\text{Mass of reactants} - \text{Mass of products})\ 931\ \text{Mev/amu}.$$

b. If the mass of reactants is greater than the mass of the products, mass is lost during the course of the reaction. Energy is therefore released. The reaction is called exoergic if energy is released (Q greater than zero).

c. If the mass of the reactants is less than the mass of the products, mass must be supplied in order for the reactions to go as written (Q less than zero). The only way for mass to be supplied is by the destruction of energy. Then, at least -Q (here Q is negative, so -Q is positive) amount of energy must be supplied to the reactants to make the reaction go as written. This amount of energy, -Q is called the threshold energy. When $Q < 0$ and energy must be supplied to make the reaction go as written, the reaction is said to be endoergic.

118. CALCULATION OF Q

a. The calculation of Q is a relatively easy matter if one has a table of the masses of nuclei. A table of nucleon masses is generally not available; however, the usual tables of isotopic masses including the mass of the electrons (appendix V) can be readily used. Note that we always have conservation of Z for any nuclear reaction. Thus, if we used elemental masses, we will not be making any error since the same number of electrons appear on both sides of the equation, and there will not be any electrons created or destroyed.

$${}_0n^1 + {}_5B^{10} \longrightarrow {}_2He^4 + {}_3Li^7 + Q$$

Mass of the reactants: ${}_0n^1$ = 1.00894 amu

${}_5B^{10}$ = 10.01618 amu

Reactants = 11.02512 amu

Mass of products: ${}_2He^4$ = 4.00390 amu

${}_3Li^7$ = 7.01822 amu

Products = 11.02212 amu

$$Q = 931\,\frac{\text{Mev}}{\text{amu}}\,(11.02512\ \text{amu} - 11.02212\ \text{amu})$$

$$= 931\,\frac{\text{Mev}}{\text{amu}} \times 0.00300\ \text{amu} = 2.79\ \text{Mev}$$

Note that Q is positive. This means that energy will be released during the reaction by a destruction of 0.00300 amu of mass. The reaction is exoergic.

b. Problem: Calculate Q for the following reactions:

(1) ${}_2He^4 + {}_4Be^9 \longrightarrow {}_6C^{12} + {}_0n^1 + Q_1$

(2) ${}_2He^4 + {}_4Be^9 \longrightarrow {}_5B^{12} + {}_1H^1 + Q_2$

(3) ${}_2He^4 + {}_4Be^9 \longrightarrow {}_5B^{10} + {}_1H^3 + Q_3$

Answers: Q_1 = 5.74 Mev, Q_2 = -7.64 Mev, and Q_3 = -13.28 Mev.

c. In reaction (2), the alpha particles would have to be accelerated to at least 7.64 Mev in order to get the reaction to go as written. In reaction (3), at least 13.28 Mev of energy would have to be supplied to the reactants to get the reaction to go as written. Thus, 7.64 Mev and 13.28 Mev are the threshold energies. Both reactions are endoergic.

119. PROBABILITY OF THE OCCURRENCE OF REACTIONS

a. The relative probability of a reaction to occur in a set of reactions with the same reactants can be estimated from the Q's of the reactions. The reaction with the highest positive Q value will usually be the most probable. Reactions with negative Q's will be least probable.

b. Consider the reactions illustrated above. Reaction (1) is the most probable since we do not have to supply energy to get the reaction to go. Reaction (2) is the next most probable; and (3) is the least probable. If 7.64 Mev of energy is supplied, only (1) and (2) can occur. But (1) will still be the most probable. If 13.28 Mev of energy is supplied, all the reactions can occur; (1) will predominate, (2) will be the next most prominent, and (3) will be the least probable reaction. Thus, the probability order, based on a Q scale, will hold for all energies. This probability relationship is called the Q rule.

c. We note here that the Q rule is a rule of thumb and many examples are known which violate this rule. Strictly speaking, we should know what sort of potential barrier there is for each possible reaction before a probability estimation is attempted. In addition to the potential barrier, thermodynamic considerations (entropy and free energy) should be consulted. The problem, on the whole, is extremely complex.

120. CROSS SECTION

a. Probabilities for the occurrence of nuclear reactions are of great importance in nuclear physics. For this reason, quantitative measures of reaction probability are required. A measure of the probability of reaction occurrence (not strictly a true probability) is the cross section.

b. One can perhaps better grasp the concept of cross section by use of physical analogies rather than strict mathematical derivations. Let us consider the following case. Suppose a machinegun is locked into a given position and is firing at a target. The target will consist of two parts, an outer ring and a bull's-eye. The machinegun is assumed to have a fixed rate of fire. The assumption is also made that all bullets will hit the target in a random manner. For any given rate of fire, there will be a certain number of bull's-eyes for a given time interval. The probability of hitting the bull's-eye will be the ratio of the number of bull's-eyes obtained to the total number of shots fired. But this will also be the ratio of the area of the bull's-eye to the total area of the target since the pattern of shots is assumed to be random. If the total area of the target is taken as unity, then a measure of probability of hitting the bull's-eye is just the area of the bull's-eye.

c. In a similar way, consider the area of the nucleus as seen by the bombarding particles, then a measure of the probability for reaction is a cross-sectional area. Let us expand this notion with another analogy to give some other characteristics of reaction.

d. Again set up a machinegun firing at a target. This time assume the target to be a cotton bale with steel balls imbedded within. Also, assume that the projectiles are of a strange material which will at times stick to the steel balls and not at other times and that the projectiles will completely go through cotton if there are no collisions with steel balls. We can now see a property of nuclear reactions. The number of "sticks" are going to depend on the density (number of balls per unit volume) of steel balls and the properties of the projectiles and the targets. This is a property of nuclear reactions.

e. If a unit area is picked, then the probability for reaction can be measured as the effective area for shots (or incident particles) that cause the reaction, in the same way as the area of the bull's-eye is a measure of the probability of hitting the bull's-eye. However, the effective area or cross section may be larger than the unit area.

f. The unit area is rather arbitrarily chosen as 10^{-24} cm^2. This is of the same order of magnitude as the area cut by a plane passing through the diameter of a typical nucleus. This unit is defined as the barn; 1 barn = 10^{-24} cm^2. All nuclear cross sections will be measured in barns.

g. One should note that the cross section will depend upon the material being bombarded, the bombarding particle, the energy of the bombarding particle, and the particular reaction being considered; thus, the cross section for scatter will be different than that for capture, etc.

h. The symbol for cross section is σ. The total cross section is:

$$\underset{\text{Total}}{\sigma_t} = \underset{\text{Scatter}}{\sigma_s} + \underset{\text{Capture}}{\sigma_c} + \underset{\text{Fission}}{\sigma_f} + \ldots$$

121. MEAN FREE PATH

a. The mean free path for reaction is the mean distance a bombarding particle will travel once it has entered the target material. Obviously some bombarding particles will react immediately upon entering the target material while a few will be able to travel an appreciable distance before reacting.

b. This distance traveled will depend upon the density (number of atoms per unit volume) of the target material, since there will be more collisions the greater the density is, and hence a shorter mean free path. The distance traveled will also depend on the probability for reaction (cross section). Hence, the larger σ is, the shorter the distance is. The relationship is:

$$\lambda = \frac{1}{N\sigma}$$

where λ is mean free path, N is density in atoms/cm^3, and σ is in cm^2 to give λ in cm. Note that, although λ is a function of the density, σ is independent of density.

c. The mean free path will also depend upon the reaction being considered. The total mean free path is given by:

$$1/\lambda_t = 1/\lambda_s + 1/\lambda_c + 1/\lambda_f + \ldots$$

and

$$\lambda_t = \lambda_c + \lambda_s + \lambda_f.$$

d. Example: The thermal neutron capture cross section for cadmium is 7100 barns. What is the mean free path of a thermal neutron in Cd? The density of Cd is 8.64 gm/cm^3.

$$\sigma c = 7100 \text{ barns} = 7.1 \times 10^{-21} \text{ cm}^2$$

$$N = 8.64 \text{ g/cm}^3 \times \frac{1}{112 \text{ g/gaw}} \times 6.02 \times 10^{23} \frac{\text{atoms}}{\text{gaw}}$$

$$\lambda_c = \frac{112}{7.1 \times 10^{-21} \times 8.64 \times 6.02 \times 10^{23}} \text{ cm}$$

$$\lambda_c = 3.03 \times 10^{-3} \text{ cm}$$

122. RESONANCE REACTIONS

Because nuclei have discrete energy levels, there are conditions for which reaction probability can be extremely large. That is, it is possible to supply just the proper amount of energy to the reactants so that a very high cross section for reaction can occur. Essentially, the proper amount of energy is introduced so that the compound nucleus can be excited to a higher energy level. Reaction probability then increases. The energy for which this occurs is called the resonance energy. The peak in the cross section versus energy curve is called the resonance peak.

123. PROBLEMS

a. What is the compound nucleus for ${}_7N^{14}$ (α, p) reaction? What is the product of this reaction?

b. Calculate Q for: ${}_4Be^9$ (α, n) ${}_6C^{12}$.

c. Calculate Q for the reaction: ${}_1H^3 \longrightarrow {}_2He^3 + \beta^-$.

d. The total cross section for a nuclear reaction is 0.6 barns. The scatter cross section is 0.45 barns, and the capture cross section is 0.05 barns. What is the fission cross section?

e. A certain material has a density of 5.65 gm/cm^3. It has a gaw of 350 gm/mole. The thermal neutron capture cross section is 0.5 barn. What is the mean free path of neutrons in this material?

SECTION II. NEUTRON REACTIONS

124. HISTORICAL

a. The discovery of the neutron took place in several distinct stages. The earliest recorded observations involving the neutron dates to the early 1930's in an experiment in which alpha particles were used to bombard beryllium metal. A resulting extremely penetrating radiation was obtained. The fact that radiation was given off was evidenced by secondary effects. The source of the alpha particles was ${}_{84}Po^{210}$.

b. The second stage was an attempt to identify the penetrating radiation which resulted from the beryllium bombardment. Paraffin blocks placed in the path of the penetrating radiation emitted protons which were readily identified. However, the penetrating radiation itself was not identified.

c. The indentification of the neutron itself came next. The simple experiments which identify the charge on a particle failed to detect any charge. The charge on the particle is therefore zero. The problem was to determine the mass of this charge-less particle. The mass was determined by an analysis of the recoil energy of particles involved in neutron reactions.

d. Of course, the difficulty in the identification of the neutron was the fact that it had zero charge. The mass, as determined from recoil experiments, was not accurately known but was determined to be about the same as a proton.

125. MASS OF THE NEUTRON

The accurate determination of the mass of the neutron was obtained from the energy balance of a nuclear reaction. The nuclear reaction used is the photo disintegration of the deuteron by gamma radiation:

$${}_1H^2 + {}_0\gamma^0 \longrightarrow {}_1H^1 + {}_0n^1.$$

The minimum energy of the γ ray needed to break up the deuterium atom is 2.21 Mev. This corresponds to 0.00238 amu in mass.

$$\begin{aligned} M({}_0n^1) &= M({}_1H^2) + 0.00238 - M({}_1H^1) \\ &= 2.01472 + 0.00238 - 1.00813 \\ &= 1.00897 \text{ amu.} \end{aligned}$$

More recent determinations have yielded 1.00894 amu for the mass of the neutron.

126. ENERGY CLASSIFICATION OF NEUTRONS

The classification of neutrons is a fairly arbitrary affair. However, since the cross section for reaction depends very much on the kinetic energy of the neutron, a classification based on this energy is a useful device. See table 6.

Table 6. Energy Classification of Neutrons

Name	Energy Range
Thermal neutrons	1/40 to 1/30 ev
Slow neutrons	1/30 to 100 ev
Intermediate neutrons	100 to 0. 1 Mev
Fast neutrons	> 0. 1 Mev

127. NEUTRON SOURCES

Since neutron reactions are of utmost importance in nuclear physics, available sources of neutrons are needed. Listed below are a number of general reactions which will yield neutrons of various energy classes.

a. (γ, n) Reactions. The photo disintegration of deuterons which was used for mass determination of the neutron is a classic example.

$$_1H^2 + {}_0\gamma^0 \longrightarrow {}_1H^1 + {}_0n^1$$

Neutrons of various energy classes can be obtained depending on σ and the energy of the γ ray. For (γ, n) reactions, Q is invariably negative, and energy must be supplied with the γ ray. A good source is also the reaction $_4Be^9$ (γ, n) $_4Be^8$ with a minimum γ energy of 1.62 Mev. The $_4Be^8$, in turn, is radioactive.

b. (α, n) Reactions. The classic example is the alpha particle bombardment of Be-9 ($_4Be^9$ (α, n) $_6C^{12}$). The neutrons ejected in this reaction are of about 5. 5 Mev energy. Another example of the (α, n) reaction is:

$$_{13}Al^{27}\ (\alpha,\ n)\ _{15}P^{30}$$

c. (d, n) Reactions. The reaction $_4Be^9$ (d, n) $_5B^{10}$ is a useful source of neutrons. The deuterons are accelerated in a cyclotron. $_3Li^7$ (d, n) $_4Be^8$ gives neutrons up to 15 Mev. $_1H^2$ (d, n) $_2H^3$ gives neutrons up to 3. 2 Mev. Other examples of the (d, n) reaction, which might be used as sources, are:

$$_3Li^6\ (d,\ n)\ _4Be^7$$

$$_{52}Te^{130}\ (d,\ n)\ _{53}I^{131}$$

$$_{83}Bi^{209}\ (d,\ n)\ _{84}Po^{210}$$

$$_{26}Fe^{56}\ (d,\ 2n)\ _{27}Co^{56}$$

$$_{52}Te^{130}\ (d,\ 2n)\ _{53}I^{130}.$$

d. (p, n) Reaction.

$$_{11}Na^{23} + {}_{1}H^{1} \longrightarrow {}_{12}Mg^{23} + {}_{0}n^{1}.$$

Reactions of the (p, 2n) variety have also been observed using very high-energy protons.

e. Fission Reaction. This reaction provides the largest available neutron fluxes. It is often carried out in a nuclear reactor or pile. The fission reaction chosen is usually the slow neutron fission of U-235 or Pu-239. Two to three neutrons are ejected for each fission that occurs. The neutrons ejected from U-235 fission have a mean energy of about 0.8 Mev.

128. NEUTRON INDUCED REACTIONS

a. Since the neutron has no charge associated with itself, the problem of penetrating a target nucleus is a relatively easy matter. It should be stressed that in addition to particles ejected, or gamma emission which is evolved during the neutron reaction, there is, in a great many cases, a radioactivity associated with the daughter nucleus. This is called neutron induced radioactivity. As a important example, fission fragments are, in general, radioactive.

b. Thermal Neutron Reactions. A large variety of neutron reactions can occur depending mainly on the cross section for a particular reaction. The reactions considered in this section have fairly large cross sections for thermal neutrons.

(1) $(n,\ \gamma)$ Reactions. These are in the radiative capture class (sometimes called simply absorption). There are a huge number of specific reactions in this category. The following are two examples of great importance in nuclear physics:

$$_{5}B^{10}\ (n,\ \gamma)\ _{5}B^{11}$$

$$_{48}Cd^{112}\ (n,\ \gamma)\ _{48}Cd^{113}.$$

Both of these materials have unusually large neutron capture cross sections. Thus, these materials can be used to control the population of neutrons in a given volume of material. There are a few other materials with larger capture cross sections than cadmium or boron, but these are not found in abundance. Figure 57 shows the variation of σ with energy for cadmium and boron.

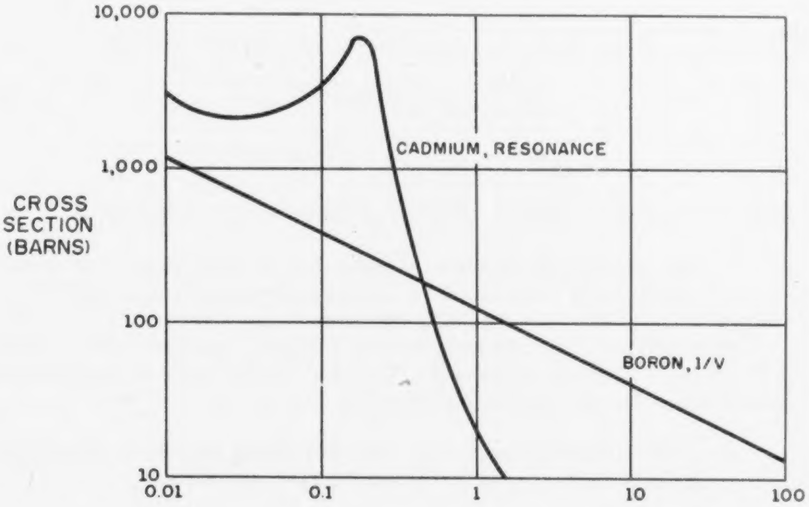


Figure 57. Cross Section for Boron and Cadmium

(2) (n, p) Reactions. Reactions of this variety and of the (n, d) can and do occur. The (n, d) reactions are generally less probable than the (n, p) reactions for slow neutrons. Examples of the (n, p) reactions are:

$${}_{7}N^{14}\ (n,\ p)\ {}_{6}C^{14}$$

$${}_{16}S^{32}\ (n,\ p)\ {}_{15}P^{32}$$

$${}_{29}Cu^{65}\ (n,\ p)\ {}_{28}Ni^{65}$$

(3) (n, α) Reactions. The cross sections for some (n, α) reactions are fairly large for slow neutrons. ${}_{3}Li^{6}$ (n, α) ${}_{1}H^{3}$ can be used for a source of ${}_{1}H^{3}$. ${}_{5}B^{10}$ (n, α) ${}_{3}Li^{7}$ is used for neutron detectors of the ionization chamber type. The reactions:

$${}_{7}N^{14}\ (n,\ \alpha)\ {}_{5}B^{11}$$

$$_{8}O^{16}\ (n,\ \alpha)\ _{6}C^{13}$$

$$_{11}Na^{23}\ (n,\ \alpha)\ _{9}F^{20}$$

$$_{13}Al^{27}\ (n,\ \alpha)\ _{11}Na^{24}$$

also occur. Many of the daughter nuclei are radioactive as:

$$_{9}F^{20} \longrightarrow {}_{10}Ne^{20} + {}_{-1}\beta^{0}$$

$$_{11}Na^{24} \longrightarrow {}_{12}Mg^{24} + {}_{-1}\beta^{0}.$$

These are typical examples of neutron induced radioactivity.

(4) Fission Reactions. Probably the most important neutron reaction is the fission reaction. Fission is discussed in more detail in chapter 7. U-235 and Pu-239 both have large fission cross sections for slow meutrons. Cross sections for capture, scatter, and fission for U-235 are given in chapter 7. U-238 does not have an appreciable cross section for fission for neutrons of energy below 1 Mev.

c. Fast Neutron Reactions. The following group of reactions have reasonably large cross sections for fast neutrons.

(1) (n, n) Reactions. Here are grouped the elastic and inelastic scattering reactions. These particular reactions will be discussed in detail later.

(2) (n, 2n) Reactions. There are many cases in which the capture of a fast neutron has resulted in the emission of two neutrons. In most cases, the product nucleus is unstable. For example:

$$_{19}K^{39}\ (n,\ 2n)\ _{19}K^{38}$$

$$_{19}K^{38} \longrightarrow {}_{18}A^{38} + {}_{+1}\beta^{0}$$

$$_{51}Sb^{121}\ (n,\ 2n)\ _{51}Sb^{120}$$

$$_{51}Sb^{120} \longrightarrow {}_{50}Sn^{120} + {}_{+1}\beta^{0}.$$

(3) Fission. Fast neutron fission occurs with U-238. The cross section for fission of U-238 is zero for low-energy neutrons, but gets very large for higher energy neutrons. Some fission will occur with neutrons down to 1 Mev energy.

d. Variation of Capture Cross Section With Velocity.

(1) The variation of capture cross section with velocity of the incident particle is, in general, inversely proportional to the velocity of the incident particle; that is, as the incident particle velocity increases, the capture cross section will decrease and vice versa. This rule can be expressed as:

$$\sigma \alpha \frac{1}{V}.$$

It is a reasonably good rule which holds where V is the velocity of the incident particle over a great range of velocities. It is not a general law, in that many variations occur and the rule does not hold at very low velocities. The 1/V relationship is a hyperbola, as in figure 58.

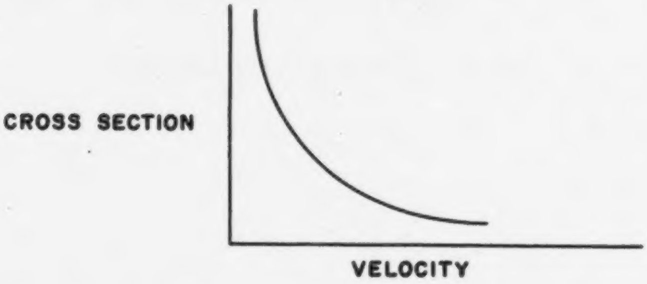


Figure 58. σ Versus V

(2) The capture cross section for boron follows a 1/V law quite well. The 1/V law also applies reasonably well for slow neutron fissioning of U-235. For this reason, one would want to slow the 0.8 Mev neutrons ejected from a fission (process of moderation) in order to increase the cross section for using these neutrons to provide further fission.

(3) The 1/V law definitely does not hold for fast neutron fissioning, nor does it hold even reasonably well for reactions other than capture and slow neutron fissioning.

e. Resonance Reactions.

(1) The 1/V variation of capture cross section is a reasonably good rule. However, it sometimes breaks down at relatively low velocities where the cross section may suddenly rise sharply.

Figures 59 and 60 illustrate the capture cross section of cadmium and the total cross section of indium.

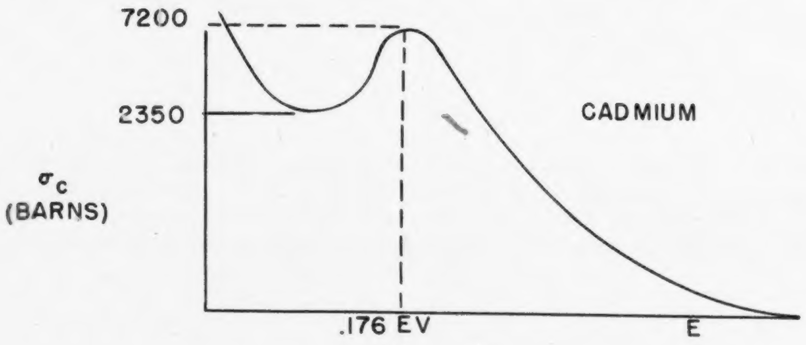


Figure 59. Capture Cross Section for Cadmium

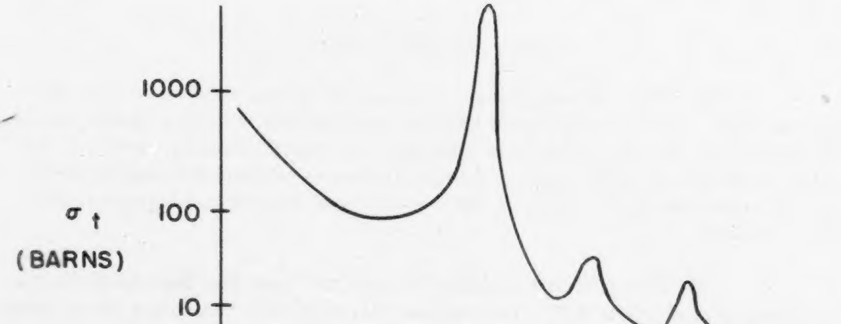


Figure 60. Total Cross Section for Indium

(2) Note that these rises of cross section (therefore, reaction probability increases) are very sharp. This means that at certain sharply defined energies, the reaction probability increases very rapidly. Note, also, that these sharp rises are superimposed on the 1/V variation which is normally expected. The sharp rise in cross section at a particular energy is called a resonance. The reaction which occurs is the resonance reaction. The particular energy at which it occurs is the resonance energy.

(3) That resonance exists is a manifestation of the fact that nuclear energy levels are discrete. When resonance occurs, just the proper amount of energy is carried by the incoming particle to raise the compound nucleus to a higher energy level. Great use can be made of the resonance in reactions since it is possible to obtain far greater reaction probabilities by proper choice of the energy of the bombarding particles.

f. Scattering and Moderation.

(1) These are essentially (n, n) reactions. The need for moderation has been discussed in the preceding section.

(2) A moderator is a material which will slow neutrons down to the thermal energy range. What is wanted then is a material with a high-scatter cross section in which a great deal of the neutron momentum is transferred to the moderating material. To achieve high momentum transfer, one should use a very low mass number (A) with a large density. The large density assures a small mean free path. It would be better to have inelastic collision rather than elastic collisions, since more energy would be lost per collision on the average. However, low mass number elements do not have large inelastic scatter cross sections. Even when using an ideal material, it would take a large number of collisions to slow fast neutrons down to thermal energy ranges.

(3) Good moderating materials are heavy water, graphite, and ordinary water. Liquid hydrogen and deuterium would be ideal except for the hazards involved in handling such materials.

(4) Another scattering reaction application is for the use of neutron reflectors. Neutron reflectors are used to keep extraneous loss of neutron populations from a given volume to a very low level. For this application, a material of large mass number (A) is wanted in order to transfer very little of the neutron's momentum to the reflector. Again, a dense material is needed to keep the mean free path down.

(5) There is, however, an exception to the rule for reflector scattering. Beryllium has such a large elastic scatter cross section that momentum transfer is far outweighed in the final effect. Thus, beryllium is used for neutron reflectors.

129. NEUTRON DETECTORS

a. All neutron detectors are essentially secondary effect instruments; that is, they rely on a nuclear reaction to provide either charged particles or gamma radiation. This secondary radiation is measured. From this measurement, the number of neutrons can be determined.

b. Reactions which yield such emission are (n, γ), (n, p), (n, α), and (n, fission). The resulting particles are then detected by ionization chambers, Geiger counters, or scintillation detectors.

c. (n, γ) reactions are detected with Geiger counters or scintillation counters. Any of the detectors can be used for the other reactions.

d. An (n, α) reaction very commonly used for detectors, particularly for ionization chambers is:

$$_5B^{10}\ (n,\ \alpha)\ _3Li^7.$$

Commonly the chamber is filled with BF_3 gas. The ionization in the chamber is caused by the emitted alpha particle.

e. Fission chambers are a rather common neutron detector. Here the dense ionization of the fission fragments produced by neutron induced fission can be easily measured in an ionization chamber.

f. The detection of fast neutrons presents a more difficult problem. Ideally, one would like to use a fission chamber with pure U-238; however, the cost is prohibitive. There is enough U-235 present in natural uranium to provide enough material for slow neutron fission.

g. The following scheme for detection of fast neutrons is used. An outside layer (several mean free paths of slow neutrons thick) of high-capture cross section for slow neutrons is used. This stops the slow neutrons but lets the fast neutrons through. The fast neutrons can then be slowed down and react in any of the systems mentioned above for thermal neutrons. The number of reactions then occurring is proportional to the original number of fast neutrons.

130. PROBLEMS

a. Boron has a capture cross section which has a 1/V dependence. For 10 ev neutrons, the cross section is 30 barns. What will the cross section be for thermal neutrons (1/40 ev)?

b. Suppose Cd has a capture cross section that follows a 1/V law. σc = 20 barns for neutrons of 1 ev energies. What would the σc be for 0.2-ev neutrons? The resonance for capture occurs at 0.2 ev. σc is actually 7000 barns. Compare this figure with your answer.

CHAPTER 7

FISSION, FUSION, AND CHAIN REACTION

SECTION I. FISSION

131. HISTORICAL

a. In the middle 1930's, many experimenters were using the newly discovered neutron to induce nuclear reactions. Particular interest was exhibited in bombarding the heavier nuclei with these particles. E. Fermi was particularly active in such work; and upon irradiating uranium with neutrons, he found several unknown β^- activities. These were believed to be transuranic elements, i.e., elements whose atomic number is greater than 92.

b. It was not until 1939 that the true nature of these β^- emitters was determined. Hahn and Strassman, repeating the experiments of Fermi, did very careful chemical analysis of the bombarded material. They found that some of the β^- activities were due to isotopes of barium and lanthanum.

c. It remained for L. Meitner, in conjunction with O. Frisch, to recognize the significance of these findings. They stated that when a neutron reacted with uranium, the heavy element "fissioned" or broke up into two nuclei of intermediate atomic number with the release of a large quantity of energy.

d. Later many physicists turned their attention toward this phenomenon, and a large amount of experimental data was obtained. Nier and Dunning showed that it was only the U-235 isotope that was fissioned by thermal neutrons. This agreed with the Bohr and Wheeler fission theory that had been published previously.

e. Considerable interest was aroused in the use of the fission process as a source of power when it was realized that the energy release per fission was of the order of hundreds of Mev. With the approach of World War II, a shroud of secrecy descended on much of the research in this field which hardly rose until the detonation of an atomic bomb at Hiroshima.

132. FISSION PROCESS

a. It is of interest to see just why we can get relatively large amounts of energy released during the fission process. Let us reexamine the curve originally presented in paragraph 88 showing the variation of binding energy per nucleon with atomic mass number A. Remembering that binding energy is really a negative energy, we can invert the curve to get a more graphic view of the relative stability of nuclei.

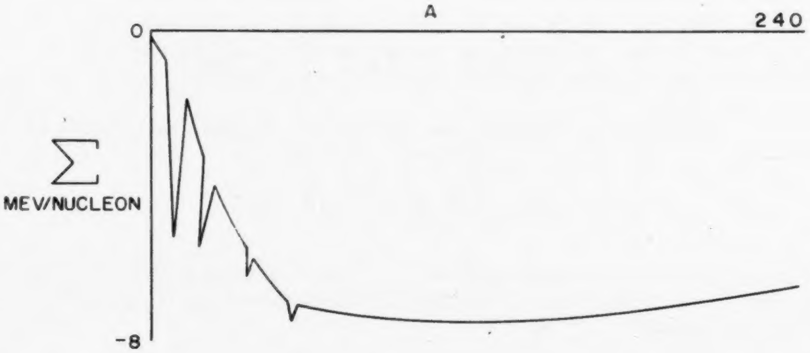


Figure 61. Binding Energy Per Nucleon

b. We can see that a nucleus of mass 240 has a binding energy of about -7.5 Mev/nucleon while one of mass 120 has -8.3 Mev/nucleon. Thus, if we could somehow get a heavy nucleus (A ~ 240) to split into two lighter ones, we would have: (-7.5) - (-8.3) or 0.8 Mev/nucleon released as usable energy. Since there are 240 nucleons, the total energy released per split would be about 240 nucleons x 0.8 Mev/nucleon = 192 Mev.

c. This, then, is the process of fission; the splitting of a heavier nucleus into two or more lighter ones with resulting energy release. It should be noted that no whole nucleons are either created or converted into energy. Instead, only the average binding energy (or average mass) of the nucleons is changed; the large amount of energy released per reaction is due to the large number of nucleons involved.

d. As mentioned previously, fission is often initiated by bombarding neutrons. Although it can occur in other ways, neutron induced fission is probably the most common.

e. Some interesting facts about the particles resulting from fission can be obtained by use of the n/p ratio. In chapter 4, it was mentioned that relatively stable nuclides with very large A have a value of about 1.5 for n/p while only about 1.3 for an A of 120. The products formed immediately after fission called fission fragments would have an n-to-p ratio which is too high for their atomic mass and thus have an excess of neutrons. This tends to make them unstable, emitting β^- particles and, in some instances, neutrons.

133. THERMAL NEUTRON FISSION

a. Although many nuclei can be fissioned in various ways, the main ones of interest are those that can be fissioned by thermal neutrons. These include: $_{92}U^{233}$, $_{92}U^{235}$, and $_{94}Pu^{239}$.

b. The general equation for neutron fission may be written as follows:

$$_0n^1 + X \longrightarrow 2\ ff's + v\ _0n^1 + Q$$

where X is the fissionable nucleus, 2 ff's are the two fission fragments formed, v is the number of neutrons emitted upon fission, and Q is the energy released.

c. For thermal neutron fission of a $_{92}U^{235}$, we have:

$$_0n^1 + {}_{92}U^{235} \longrightarrow 2\ ff's + 2.5\ _0n^1 + 180\ \text{Mev}$$

d. The values of v and Q are average values. The nucleus will not always split in exactly the same way; and therefore, the number of neutrons given off as well as the exact nature of the fission fragment nuclei will vary. The best unclassified value of v for $_{92}U^{235}$ is 2.5; $_{94}Pu^{239}$ has v equal to 3.0. Both of these values are for fission induced by thermal neutrons.

134. INDUCING FISSION

a. Since energy is released upon fission and the fission fragments have a greater binding energy than the original nucleus, the fission reaction would be expected to go spontaneously, and to a small extent it does. However, it is usually necessary to excite the fissionable nucleus, i.e., give it a certain amount of extra energy, before it will fission. Thus, the original nucleus is relatively stable to fission in its ground state; but when excited beyond a certain point, it will fission readily.

b. The excitation energy may be given to the nucleus in many ways. One is to bombard it with high-energy photons. This causes photofission, and the minimum energy gamma that will produce this result gives an indication of the excitation energy required of different nuclei. See table 1.

Table 1

Nuclide	Photofission Threshold
Th-230	5.40 Mev
U-233	5.18 Mev
U-235	5.31 Mev
U-239	5.08 Mev
Pu-239	5.31 Mev

c. Another means of producing fission is by striking a nucleus with high-energy charged particles such as very fast α particles. This will result in inelastic scattering possibly exciting the nucleus enough to produce fission.

d. Neutron bombardment is the most common method of causing fission. Here the neutron is absorbed in the original nucleus forming a compound nucleus. Even if the neutron is in the thermal range and has little kinetic energy, the compound nucleus is highly excited due to binding energy of the neutron.

e. For example, the stable U-236 nucleus has a higher total binding energy (not per nucleon) than U-235. Therefore, a free neutron entering U-235 forms the compound nucleus which is excited by this difference in total binding energy. The following calculations show the net excitation energy assuming the kinetic energy of the original neutron is small:

$$ {}_0n^1 + {}_{92}U^{235} \longrightarrow ({}_{92}U^{236}) $$

Mass of n + Mass of U-235 - Mass of U-236 = Excitation Energy

$$1.00894 + 235.1133 - 236.11493 = 0.00731$$

$$= 931 \times 0.00731 = 6.8 \text{ Mev}$$

f. The actual energy required to initiate fission in U-235 is only about 5.3 Mev (table 1). In this case, the binding energy of the neutron alone is sufficient to cause fission. In other cases (e.g., $n + {}_{92}U^{238}$), the binding energy of the neutron is not large enough. However, if the entering particle has kinetic energy, this too goes to excite the nucleus. Therefore, the sum of the kinetic energy of the neutron plus its binding energy in the compound nucleus must be greater than the required activation (or threshold) energy to cause fission.

135. LIQUID DROP THEORY

a. The mechanism by which these heavy nuclei fission was propounded by Bohr and Wheeler using a liquid drop model. The collective behavior of all the nucleons can be approximated by considering the nucleus to be composed of an essentially incompressible fluid. The nucleus then acts like a drop of this fluid; the surface tension (due to nucleon-nucleon forces) tending to hold it together with the smallest area (spherical), and the coulombic forces (due to the protons) tending to break it up.

b. Normally, the nucleus is in its minimum energy level, i.e., spherical form. If it is excited by some means, it will start to oscillate through various shapes going first into ellipsoidal and then a "dumbell" form, and if the energy is not sufficient, back again until the excess energy is given off, probably in the form of gamma rays. However, if the excitation is quite large, the dumbell may neck down until the width is zero, at which time there are effectively two nuclei each positively charged which repel each other.

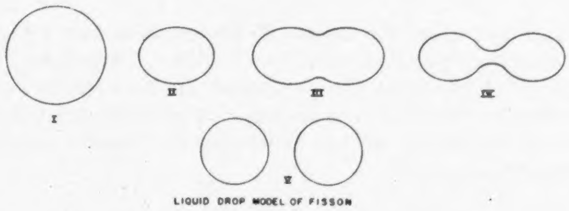


Figure 62. Liquid Drop Model of Fission

c. Calculations, using this model, agree quite well with experimental data.

d. The threshold energy required to produce fission may be calculated using the liquid drop model. These values and the excitation energy due to binding of a neutron are shown in the following table.

Table 2

Target Nucleus	Compound Nucleus	Excitation Energy From Thermal Neutron	Required Threshold Energy
U-233	(U-234)	6.6 Mev	4.6 Mev
U-235	(U-236)	6.4 Mev	5.3 Mev
U-238	(U-239)	4.9 Mev	5.5 Mev
Th-232	(Th-233)	5.1 Mev	6.5 Mev
Pa-231	(Pa-232)	5.4 Mev	5.0 Mev
Np-237	(Np-238)	5.0 Mev	4.2 Mev
Pu-239	(Pu-240)	6.4 Mev	4.0 Mev

e. From the figures given in table 2, the possibility of neutron-induced fission can be ascertained. If the excitation due to binding of a neutron alone is greater than the required activation or threshold energy for fission, absorption of a neutron with no kinetic energy may produce fission. If, however, the threshold energy is the larger, it is necessary that the neutron have sufficient kinetic energy to make the total of neutron binding energy from absorption plus kinetic energy greater than the threshold energy for fission. This criteria and the data from table 2 show that all the target nuclei listed except U-238 and Th-232 can be fissioned by thermal neutrons. On the other hand, to fission U-238, a neutron whose kinetic energy is at least 5.5 - 4.9 = 0.6 Mev would be required.

136. FISSION PRODUCTS

a. The U-235 nucleus has been found to yield at least 30 different pairs of nuclides upon fission. The nuclei formed immediately upon fission are the fission fragments.

b. The fission fragments generally have too high an n/p ratio and usually emit β^- particles to decrease this ratio. The products of this radioactivity are often radioactive in the same fashion and tend to produce a chain of radioactive nuclides. These, including the initial fission fragments, are called fission products.

c. A typical fission and the resulting chain of fission products are shown below:

$${}_0n^1 + U^{235} \longrightarrow {}_{38}Sr^{94} + {}_{54}Xe^{140} + 2\,{}_0n^1$$

$${}_{38}Sr^{94} \longrightarrow {}_{39}Y^{94} \longrightarrow {}_{40}Zr^{94} \text{ (stable)}$$

$${}_{54}Xe^{140} \longrightarrow {}_{55}Cs^{140} \longrightarrow {}_{56}Ba^{140} \longrightarrow {}_{57}La^{140}$$

$$({}_{57}La^{140}) \longrightarrow {}_{58}Ce^{140} \text{ (stable)}$$

d. The probability of formation of a particular fission product from thermal neutron-induced fission is shown in figure 63. The probability in percentage of the occurrence of various products is plotted versus the mass number A. Since two nuclei are formed per fission, the summing of all the points on the curve would give 200 percent.

e. It is seen that there is a definite dip in the middle of the curves. These values represent the probability of symmetrical fission, i. e., where the two fission fragments are identical. This probability is very low, so it is evident that thermal neutrons normally cause asymmetrical fission.

f. As the energy of the fission causing neutron rises, so does the dip in the curve. With very high-energy neutrons, the curve would tend to have one maximum in the middle (due to asymmetrical fission).

137. NEUTRONS EMITTED

a. Since the n/p ratio in the products of fission is higher than that of stable nuclei, one would suspect that there is a possibility of neutron emission either during fission or by the fission products. This has proved to be the case.

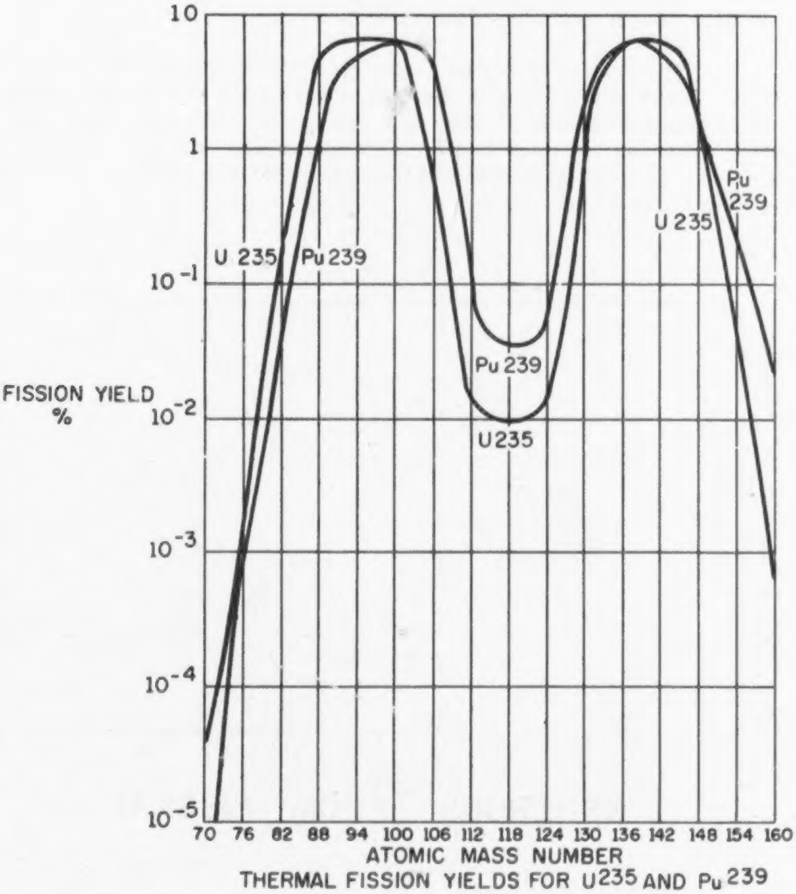


Figure 63. Thermal Fission Yields for U-235 and Pu-239

b. Most of the neutrons produced by the fission process are liberated immediately upon fission. In general, two or three neutrons are given off at this time. The exact number varies of course with the nature of the split that occurs (i. e., which fission fragments are formed). Average values for thermal neutron-induced fission for two materials have already been presented.

c. The energy of the neutrons given off in fission varies considerably. Most of them are in the fast range with a very small number even having energies of 12 Mev or higher. The average energy of the fission neutrons is 2 Mev while the most probable energy is about 0. 8 Mev. The percentage of neutrons emitted with any particular energy is shown in figure 64.

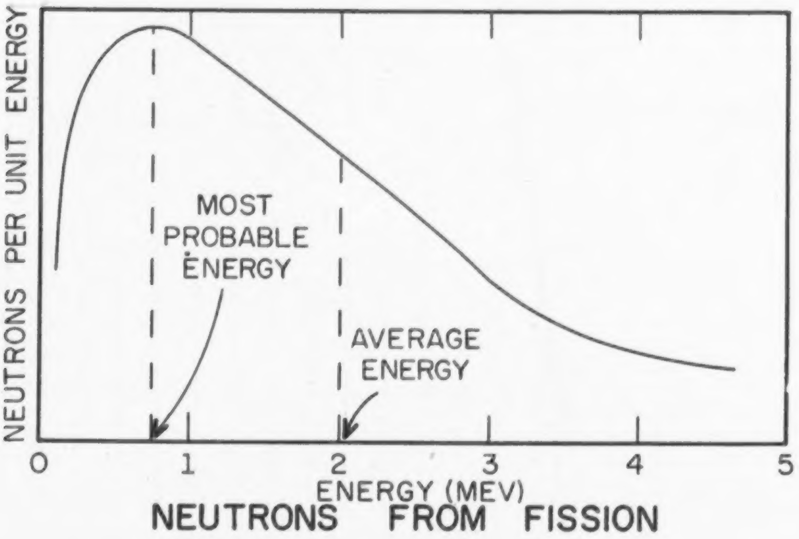


Figure 64. Neutrons From Fission

d. Neutrons that are emitted radioactively by the fission products are called delayed neutrons as compared to the prompt neutrons given during the fission process. These are less than 1 percent of the total number emitted and are given off at various times.

e. There are actually about six groups of delayed neutron emitters, and the number given off from each decays exponentially with time, the half lives varying from fractions of a second to almost a minute.

f. Although the number of delayed neutrons is small, they play a very important role in certain cases. This is particularly true in the control of nuclear reactors.

138. ENERGETICS OF FISSION

a. The total energy released due to fission may be calculated in the same way as the Q for any nuclear reaction once the manner of the split is known. Care must be taken to include, when desired, the energy of decay of the fission products. If the final stable fission products are used for calculations, all the decay energies will be included in the value of Q.

b. It is interesting to note the form in which the energy of fission release appears. Immediately after the split, the two highly charged fission fragments are in close proximity and repel each other greatly. Thus a large fraction of the total energy appears as kinetic energy of these fragments. Average values for the distribution of the total energy is shown in table 3.

Table 3. Energy Release in the Fission of U-235 by Thermal Neutrons

Kinetic Energy of Heavy Fragment	65 Mev	
Kinetic Energy of Light Fragment	100 Mev	
Total Kinetic Energy of Fission Fragments		165 Mev
Kinetic Energy of Fission Neutrons		5 Mev
Prompt γ-ray Energy		5 Mev
β^- Decay Energy		5 Mev
γ Decay Energy		5 Mev
Neutrino Energy		11 Mev
Total Energy Released		196 Mev

c. Most of this energy, especially the kinetic energy of the fragments, eventually shows up as heat energy of the medium. Thus, the energy is distributed to the slower moving atoms, and the net effect is to raise the temperature. The greater the fraction of nuclei that fission, the higher is the temperature.

139. PROBABILITY OF FISSION

a. Spontaneous fission, that is without any outside cause, will occur in all fissionable nuclei, but its probability varies considerably for different nuclides. For any given nucleus, the rate of spontaneous fission follows the same type of exponential decay law as other radioactive phenomena. The half lives for various nuclides are shown in table 4. Also shown are the number of fissions that would occur, on the average, per minute per kilogram of pure material.

Table 4. Spontaneous Fission

Nuclide	Half Life (years)	Fissions/kg/min
U-233	3.0×10^{17}	10
U-234	1.6×10^{16}	190
U-235	1.8×10^{17}	17
U-238	8.0×10^{15}	380
Pu-239	5.5×10^{15}	550
Pu-240	1.2×10^{11}	2.5×10^{7}

b. As in similar reactions, fission by neutrons may be expressed as the cross section of the nuclide in barns. The cross section will vary with the energy of the neutron, usually decreasing as the energy increases. Representative values are included in table 5.

Table 5. Thermal Neutron Cross Sections

Nuclide	σ Fission	σ Scattering	σ Capture (barns)
U-235	549	8.2	101
U-238	0	8.2	2.8
Natural U	3.9	8.2	3.5
Pu-239	664	-	361

140. PROBLEM

A certain fission process has the following equation:

$$_{0}n^{1} + {}_{92}U^{235} \longrightarrow {}_{42}Mo^{100} + {}_{50}Sn^{134} + 2\ {}_{0}n^{1}.$$

If the atomic mass of $_{50}Sn^{134}$ is 133.937 amu, how much energy is released?

SECTION II. FUSION

141. DEFINITION AND SOURCE OF ENERGY

a. Fusion is virtually the opposite of fission for it is the merger or fusion of two light nuclei into a heavier one with the release of energy. Fusion reactions are sometimes called thermonuclear reactions; the reason for this will be seen subsequently.

b. The source of energy released in fusion is the same as that for fission; a shifting or change in the huge forces that bind nucleons together. Again this is best seen on the curves of binding energy per nucleon and average mass per nucleon versus the mass number. See figure 61.

c. We can see that as A increases from 1 to 4, the binding energy decreases; that is, becomes more negative. Thus, if two nuclides with these small mass numbers are combined, the decrease in binding energy would show up as released energy.

d. This also can be shown in the average mass per nucleon curve. See figure 26. Here it can be seen, the average mass per nucleon decreases as A increases from 1 to 4. Thus, if we combine two of these nuclei with no creation or destruction of whole nucleons, the mass of the new nucleus is less than the total mass of the initial nuclei. This loss in mass is released as the equivalent amount of energy.

142. REACTIONS

a. Many different reactions may be actually classified as fusion reactions, but only a small number of these are of interest. In particular, we are interested in the reactions whose probabilities are fairly large and which do not require too large an amount of energy to initiate them.

b. Since two nuclei that are to fuse must come extremely close to one another, it is necessary that there be a minimum electrostatic repulsion between them. For this reason, we are interested in nuclei having the minimum charge, Z = 1; in other words, if a deuterium nucleus of sufficient energy strikes another deuterium nucleus, there is the possibility of two reactions:

(1) ${}_1D^2 + {}_1D^2 \longrightarrow {}_1H^1 + {}_1T^3 + Q$ (a DDp reaction),

(2) ${}_1D^2 + {}_1D^2 \longrightarrow {}_0n^1 + {}_2He^3 + Q$ (a DDn reaction).

When deuterium and tritium nuclei interact, the following reaction takes place:

$${}_1D^2 + {}_1T^3 \longrightarrow {}_2He^4 + {}_0n^1 + Q.$$

c. The values of Q may be obtained from the normal balance of masses. Thus, for the DDp reaction,

$$Q = (\text{Mass of } {}_1D^2) \times 2 - (\text{Mass of } {}_1H^1 + \text{Mass of } {}_1T^3)$$

$$= 2.01471 \times 2 - (1.00813 + 3.01702)$$

$$= 0.0427 \text{ amu} = 3.98 \text{ Mev}.$$

d. Doing similar calculations for the other reactions, the net results are:

$${}_1D^2 + {}_1D^2 \longrightarrow {}_0n^1 + {}_2He^3 + 3.24 \text{ Mev}$$

$${}_1D^2 + {}_1T^3 \longrightarrow {}_0n^1 + {}_2He^4 + 17.6 \text{ Mev}.$$

e. The energy from these reactions will appear as kinetic energy of the products. The actual energy of the individual particle can be calculated from the law of conservation of momentum. Since there are just two final particles in each reaction, they must start off in opposite directions with equal momentums. Thus,

$$m_1V_1 = m_2V_2$$

where m_1 = mass of particle 1

m_2 = mass of particle 2

V_1 = velocity of particle 1

V_2 = velocity of particle 2;

therefore,

$$\frac{V_1}{V_2} = \frac{m_2}{m_1}.$$

For the kinetic energies,

$$KE_1 = 1/2\ m_1 V_1^2$$

$$KE_2 = 1/2\ m_2 V_2^2.$$

The ratio of the kinetic energies is:

$$\frac{KE_1}{KE_2} = \frac{m_1 V_1^2}{m_2 V_2^2} = \frac{m_1}{m_2}\left(\frac{V_1}{V_2}\right)^2.$$

But from the momentum formula,

$$\frac{V_1^2}{V_2^2} = \frac{m_2^2}{m_1^2};$$

therefore,

$$\frac{KE_1}{KE_2} = \frac{m_1 m_2^2}{m_2 m_1^2} = \frac{m_2}{m_1}.$$

This indicates that the total kinetic energy is distributed between the resultant particles in amounts inversely proportional to the masses of the resultant particles. This gives a simple means for determining the kinetic energy of these particles when the total kinetic energy is known.

f. Taking the DT reaction as an example, the total kinetic energy is 17.6 Mev. The mass of $_2He^4$ is approximately 4, the mass of the neutron is approximately 1. Since the total mass of the resultant particles is approximately 5, about one-fifth (3.5 Mev) of the kinetic energy is imparted to the helium atom, and the remaining four-fifths (14.1 Mev) goes to the neutron.

g. Making similar calculations for other reactions, the equations showing the kinetic energy of the product particles is as follows:

$$_1D^2 + {}_1D^2 \longrightarrow {}_1H^1 \text{ (2.98 Mev)} + {}_1T^3 \text{ (1 Mev)}$$

$$_1D^2 + {}_1D^2 \longrightarrow {}_0n^1 \text{ (2.43 Mev)} + {}_2He^3 \text{ (0.81 Mev)}.$$

Most of the kinetic energy of the charged particles will be lost very rapidly through the ionization process. The neutron will also lose its energy in matter, but at a slower rate through scattering and other collisions.

143. PROBABILITY OF REACTION

a. As in all charged particle reactions, the probability of the occurrence of fusion in general depends on three things. These may be stated as:

(1) The probability that the two nuclei that are to react will collide at some point. In other words, they will be at the same place at the same time. This is often called the collision probability.

(2) The bombarding nucleus (it is convenient to speak of one nucleus at rest, as the target, and the other moving, as the bombarding nucleus) must be able to overcome the repulsive coulombic force of the target nucleus. To penetrate the "potential barrier," the bombarding nucleus may have enough energy to go over the top of the barrier. Even if its kinetic energy is not that great, there is still a finite probability of penetration of the barrier. This is due to the process called tunneling, where bombarding nuclei can figuratively tunnel through the barrier and appear in the nucleus. This process has already been considered in paragraph 96 on alpha decay.

b. The closer to the top of the potential barrier, the greater is the probability of tunneling. This is not a linear variation, and a small increase in kinetic energy may greatly increase the probability of barrier penetration.

c. Even though the two particles have collided and the potential barrier has been pierced, the particular nuclear reaction desired may not take place. The bombarding nucleus can pass right out again or a different, less favorable, reaction may occur. Thus, the probability of occurrence of the reaction of interest, once the penetration of the

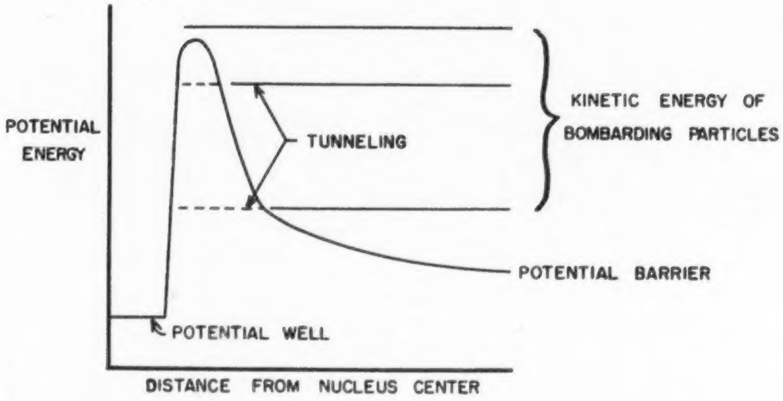

POTENTIAL ENERGY
TUNNELING
KINETIC ENERGY OF BOMBARDING PARTICLES
POTENTIAL BARRIER
POTENTIAL WELL
DISTANCE FROM NUCLEUS CENTER

Figure 65. Potential Barrier and Tunneling

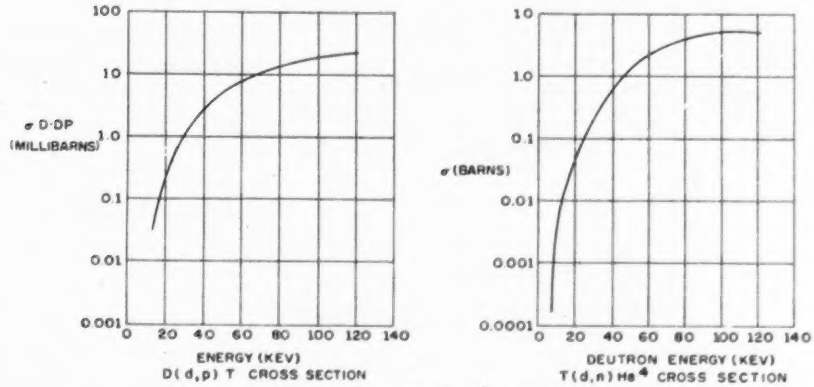
potential barrier has taken place, must be considered in determining the overall cross section or probability of the reaction.

d. The variation of the overall cross section for a particular reaction will vary considerably with the energy of the particles. This is due mainly to the change in probability of tunneling. For particles of relatively low kinetic energies, the chance of barrier penetration is so small that the reaction has an extremely small cross section.

e. The nuclei can be given sufficient kinetic energy to make barrier penetration more probable in two ways: through the use of particle accelerators, or by bringing the materials in question to a very high temperature (of the order of millions of degrees centigrade). The former method is only valid when a small number of reactions is desired, as accelerators can use only a limited number of particles. The latter system utilizes the thermal kinetic energy of nuclei in a high-temperature system, hence the term thermonuclear reactions.

f. Due to the high temperature of stars, stellar energy is produced by reactions of this type. The problem in a man-made system is how to raise the medium to the enormous temperature required.

g. The cross sections of the fusion reactions have been measured as a function of energy, and these values are presented in the two curves shown in figure 66. The DDn cross section was not plotted as it is almost the same as that for the DDp reaction.



CROSS SECTION FOR FUSION

Figure 66. Cross Section for Fusion

h. In a mass of fusible material at high temperature, the kinetic energies of all the nuclei are not the same. Some sort of distribution, possibly a Maxwell distribution, is achieved; and the cross sections in the above curve would have to be averaged over the distribution.

144. FUSION AND FISSION COMPARISON

Upon comparing fusion to the fission process, one notes certain differences:

a. Though fission releases much more energy per reaction, the energy release per mass of products is slightly greater in the fusion process.

b. In fusion, a large velocity, or kinetic energy, of the initial nuclei is usually required; while fission is usually initiated by neutrons.

c. The products of fission are usually highly radioactive; the products of fusion, aside from the long-lived tritium which is also consumed, are all stable.

SECTION III. CHAIN REACTION AND CRITICALITY

145. GENERAL

a. The possibility of production of great quantities of nuclear energy became possible upon the discovery of the fission reaction. However, as in most energy-producing reactions, something is required to initiate and to keep the reaction going.

b. In the combustion of wood in air, for example, heat or a high temperature is necessary to initiate and to keep up the reaction. This is true not only for the first part that ignites, but for all of the wood. Usually the energy produced by the initial burning heats up another part of the wood, enabling it to burn which, in turn, heats up some more of the wood, and so forth. Thus, a sort of chain develops where the heat produced by each section or part permits another section to burn and to supply more heat. This is the origin of the term chain reaction.[1]

c. In the fission process, heat is not required. Instead, neutrons are the links that form the chain. We have seen in paragraph 129 that neutron-induced fission is quite common and also that in the process of fission two or three neutrons are given off. If these fission-emitted neutrons can be used to initiate other fissions and new neutrons used to cause still other fissions, the chain will be built up. The goal is to produce energy, and this comes from fission. The neutrons are an indispensable byproduct if a large amount of energy and, hence, a large number of fissions are required.

d. Fission, however, is not the only reaction that neutrons can produce. Neutrons can be scattered, captured without producing a fission by the fissionable material, or captured by some additive or impurity in the active material without producing fission. These reactions have been discussed previously in chapter 6. Another possibility for the neutron is escape from the volume of active material; that is, it may go through the surface of the mass of fissionable material and be lost for further reactions in the fissionable material.

e. Thus, all these reactions compete with one another in any volume of active material. The success of the chain reaction depends on the fraction of fission-formed neutrons that will produce other fissions.

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[1] A more general definition of a chain reaction is "a reaction in which one of the agents necessary to the reaction is itself produced by the reaction which causes like reactions."

f. We may speak of three broad classes of chain reactions. These are called nonsustaining, sustaining, or multiplying chain reactions (the terms convergent, stationary, and divergent, respectively, are often used).

g. We may think of an operating chain reaction as a series of generations, one right after the other. A number of neutrons produce fissions which produce neutrons, some of which will cause other fissions. The ratio of the number of second generation fissions to the number of first generation fissions may be called the multiplication or reproduction factor, k. This is the same as the ratio of the number of neutrons in the second generation that produce fissions to those in the first generation that caused fissions. The k factor will be the same for every generation, provided the material, geometry, etc., do not change.

h. If the multiplication factor is less than one, the number of neutrons in each generation is less than that in the previous one. Thus, if we start out with No neutrons, the

1st generation produces No neutrons
2d generation produces k No neutrons
3d generation produces k^2No neutrons
nth generation produces k^nNo neutrons

i. With k less than one, k^n will be very small for large n; and hence, the chain reaction will tend to die out. This is a converging or nonsustaining chain reaction.

j. If k were exactly equal to one, the number of neutrons in each generation would be the same. Hence, the number of fissions per generation, or the number of fissions per unit time, since the lifetime of each generation of neutrons is approximately the same, would remain constant. This produces a chain reaction that is a constant power source and is required in the steady. state operation of a nuclear reactor or pile. Such a system has a sustaining or stationary chain reaction.

k. A multiplying or divergent chain reaction has k greater than one. Hence, if you start with No neutrons, after n generations, there will be k^nNo neutrons. The larger k is, the larger this number will be. Such a situation is required to increase the power rapidly and to obtain a large energy release in a short period of time.

l. The type of chain reaction that will take place depends, among other things, upon the total mass of fissionable material present. If there is just enough mass to produce a sustaining chain reaction, there is a *critical mass* present. If less mass is present, a *subcritical mass* which will only maintain a nonsustaining chain reaction results. Finally a *supercritical mass* will support a multiplying chain reaction.

146. INCREASING CRITICALITY

a. To increase the likelihood of a sustaining or multiplying chain reaction, minimize the reactions that compete with fission. This, of course, decreases the critical mass. Some of the means that may be used include the following:

(1) Purifying the material chemically to decrease the fraction of impurities that cause neutron capture, but do not fission.

(2) Enriching the fissile element in the isotope that fissions most efficiently and hence has less ordinary capture.

(3) Surrounding the active material with a good scattering medium which will reflect escaping neutrons back into the material.

(4) Using shapes with a minimum surface-to-volume ratio to reduce escape (a sphere is ideal).

(5) Increasing the density of the active material which also reduces the escape probability.

(6) Moderating the neutrons, i.e., slowing them down, which usually increases the fission cross section. This may be done by the inclusion of light-mass nuclei which scatter neutrons well, but this process takes considerable time and greatly slows down the reaction.

b. Also two subcritical masses could be brought together, i.e., addition of more mass. This, in general, reduces the probability of escape by decreasing the surface-to-volume ratio and tends to give a sustaining or multiplying chain reaction.

c. Figures 67, 68, and 69 graphically show a possible sequence of events in each type of chain reaction.

d. Figure 67 depicts a sample of uranium metal with impurities

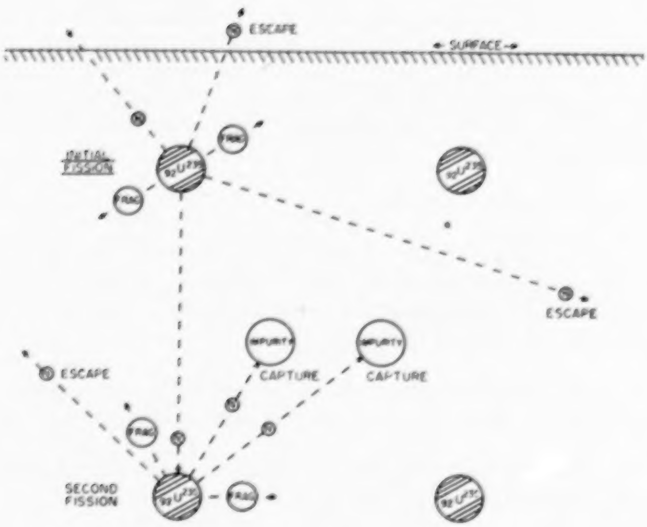
ESCAPE
SURFACE
INITIAL FISSION
FRAG
92U235
FRAG
92U235
ESCAPE
IMPURITY
IMPURITY
ESCAPE
CAPTURE
CAPTURE
FRAG
SECOND FISSION
92U235
FRAG
92U235

Figure 67. Nonsustaining Chain Reaction

capable of capturing neutrons. The initial fission produces 3 neutrons; 2 escape and 1 causes a second fission. The second fission produces 3 neutrons; 2 are captured, 1 escapes, and the chain reaction stops.

e. In figure 68, the initial fission yields 3 neutrons; 1 escapes, 1 is captured, and 1 causes a second fission. The second fission produces 3 neutrons; 2 escape and 1 causes a third fission. The third fission produces 2 neutrons; 1 escapes and 1 causes a fourth fission. The fourth fission yields 2 neutrons; 1 is captured and 1 causes a fifth fission. This example stresses that, on the average, the neutrons from 1 fission produce just 1 other fission, and the neutron population remains nearly constant.

f. In figure 69, note that fewer impurities reduce the number of neutrons lost by capture, and that closer spacing of the U-235 atoms reduces escape. On the average, two neutrons per fission cause more fissions, and the neutron population increases rapidly. (The fission fragments have been omitted from the drawing for clarity.)

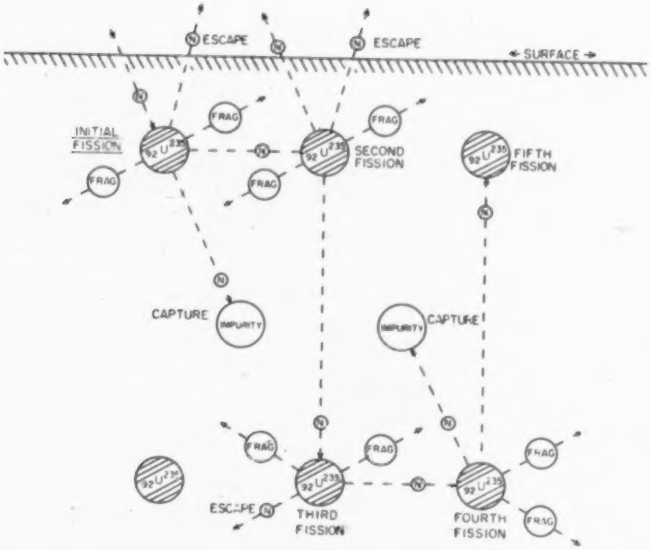
ESCAPE
N
ESCAPE
SURFACE
INITIAL FISSION
FRAG
$_{92}U^{235}$
SECOND FISSION
FIFTH FISSION
CAPTURE
IMPURITY
THIRD FISSION
FOURTH FISSION

Figure 68. Sustaining Chain Reaction

147. QUANTITATIVE TREATMENT OF CRITICALITY

a. So far, the problem of criticality has been examined qualitatively. It is now necessary to examine some simple calculations. Even here, the problem will be greatly simplified by using certain assumptions. If a more complete picture is desired, the reader should seek one or more of the advanced texts on this subject.[1]

b. In the treatment that follows, it is assumed that there are no chemical impurities in the active material that absorbs neutrons. This, of course, is never completely true, but this discrepancy could be corrected by adjusting upward the capture cross section of the fuel.

(1) If the mass of the active material is assumed to be infinite in volume, the problem of escape is eliminated (no neutrons could leave an infinite volume). The problem here is to determine how well

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[1] Elements of Nuclear Reactor Theory, Glasstone and Edlund.

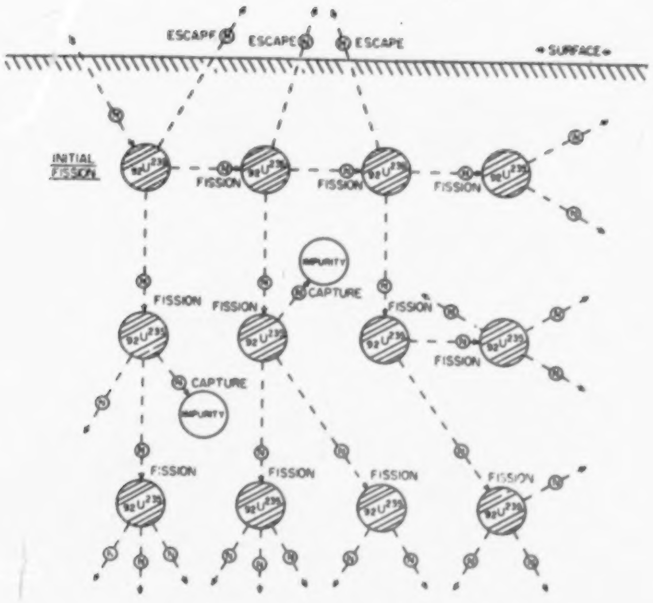

Figure 69. Multiplying Chain Reaction

the fission reaction competes with other nuclear reactions in utilizing the free neutrons in the material. There are three possibilities for any neutrons in an infinite medium: capture, scatter, or fission. These, in turn, have their respective probabilities of occurrence or cross section: σc, σs, σf. The total cross section is:

$$\sigma t = \sigma c + \sigma s + \sigma f.$$

Whenever a neutron undergoes capture, it is lost completely; in the scattering process, no neutrons are lost, but none are gained. In fission, one neutron is swallowed up. If ν is the number of neutrons released in the fission process, there is a gain of $(\nu - 1)$ neutrons. The net gain of neutrons per collision is equal to the sum of the probabilities of each reaction per collision times the number of neutrons gained or lost for that type reaction.

For capture,

$$\frac{\sigma c}{\sigma T} = \text{fraction of captures per collision}$$

$$-1 = \text{net gain of neutrons per capture}$$

$$-1 \times \frac{\sigma c}{\sigma T} = -\frac{\sigma c}{\sigma T} = \text{net gain of neutrons from capture per collision.}$$

For scatter,

$$\frac{\sigma s}{\sigma T} = \text{fraction of scatters per collision}$$

$$0 = \text{net gain of neutrons per scatter}$$

$$0 \times \frac{\sigma s}{\sigma T} = 0 = \text{net gain of neutrons per collision from scatter.}$$

For fission,

$$\frac{\sigma f}{\sigma T} = \text{fraction of fissions per collision}$$

$$(v - 1) = \text{net gain of neutrons per fission}$$

$$\frac{\sigma f}{\sigma T}(v - 1) = \text{net gain of neutrons per collision from fission.}$$

The sum of the equations is:

$$\text{Net gain of neutrons per collision} = \frac{\sigma f}{\sigma T}(v - 1) + 0 - \frac{\sigma c}{\sigma T}$$

$$= \frac{\sigma f (v - 1) - \sigma c}{\sigma T}.$$

This net gain of neutrons per collision may be called the productivity factor, f. It is, of course, directly related to the multiplication factor, k. This relationship will be discussed later. We can now determine what materials can support the different types of chain reactions by using the above equation and experimental cross sections and v values presented in section I. If f is equal to zero, there is no gain or loss of neutrons per collision; a just critical system would result. If f were greater than zero, a supercritical reaction would result; and, if less than zero, a subcritical system. It should be borne in mind that this is still for an infinite medium with no neutron escape. Consider a system composed only of $_{92}U^{235}$ and a moderating medium that causes all the fission-born neutrons to be thermalized very quickly without capture. The thermal absorption, scatter cross section, and σf values for $_{92}U^{235}$ are:

$$\sigma f = 549b$$

$$\sigma s = 8.2b$$

$$\sigma c = 101b$$

$$v = 2.5$$

Therefore,

$$f = \frac{549\ (2.5 - 1) - 101}{658}$$

$$= 1.1$$

Since f is greater than zero, it is possible for $_{92}U^{235}$ to be in a supercritical state or to sustain a multiplying neutron chain reaction. If it were desired to have $_{92}U^{235}$ in a just critical state, a finite volume could be used to allow some escape of extraneous neutrons or absorbers added to increase the effective σc and thus reduce f. Compare the productivity factor, f, to the multiplication factor, k.

f = number of neutrons gained per collision (fission, capture, and scattering)

k = number of neutrons produced per absorption (fission or capture)

$$\frac{\text{The number of collisions}}{\text{The number of absorptions}} = \frac{\sigma c + \sigma s + \sigma f}{\sigma c + \sigma f} = \frac{\sigma T}{\sigma T - \sigma s}$$

Therefore,

$$f \times \frac{\sigma T}{\sigma T - \sigma s} = \text{number of neutrons gained per absorption.}$$

If the number of neutrons gained per absorption equals the number of neutrons produced per absorption -1, then

$$f\ \frac{\sigma T}{\sigma T - \sigma s} = \text{number of neutrons produced per absorption -1}$$

$$= k - 1$$

$$\text{or,} \quad f = (k - 1) \frac{\sigma T - \sigma s}{\sigma T}$$

$$\text{or,} \quad k = 1 + f \frac{\sigma T}{\sigma T - \sigma s}$$

Since this is for an infinite medium, k_∞ is used.

$$k_\infty = 1 + f \frac{\sigma T}{\sigma T - \sigma s}$$

If σs is small compared to σT, $k_\infty = 1 + f$.

In calculating f and k_∞, it is necessary to use accurate values of the cross sections and v. To do this, consider the energy spectrum of the neutrons and the variation of cross section with energy. This is a very difficult problem. The text shall merely concern itself with average values (as in the preceding calculation of f) which, unfortunately, will not fit every situation.

(2) In a finite medium, there is a definite possibility that neutrons may leave the active material and not return. This must be considered in determining how much of a fissionable material in a given shape is required for a critical mass. To calculate accurately the effect of leakage, equations must be set up to follow the neutrons during their diffusion (i. e., scattering) throughout the medium. Consideration must be given to any moderation used during the process preceding diffusion. A detailed treatment of this subject is considered beyond the scope of this book.

148. MULTIPLICATION

a. A term frequently encountered is multiplication, M. This refers only to subcritical systems and may best be defined as the number of neutrons present at a point in a medium containing a source and fissile material divided by the number of neutrons at the same point from the source if no fissile material is present.

b. If a source of neutrons is placed in a medium containing no fissionable material, there will be a certain distribution of neutrons throughout the medium. If some fissionable material is now added to the medium, there will be an increase in the neutron density. There will still be the source neutrons, but some nuclei will fission forming new neutrons causing new fissions, etc. Thus, a nonsustaining chain reaction results; but as the initial neutron source is always present, neutrons from an effectively infinite number of generations are produced.

c. If S is the number of source neutrons emitted per unit time, there will be Sk neutrons in the first generation, Sk^2 in the second, etc. Here again, k is the multiplication factor; and since this applies only to subcritical masses, k is less than one. Therefore,

$$M = \frac{S + kS + k^2S + \ldots k^r s + \ldots}{S}$$

$$= 1 + k + k^2 + \ldots k^r + \ldots$$

By the binomial theorem,

$$M = \frac{1}{1 - k}.$$

d. We can see that as k approaches one, M approaches infinity. Therefore, it is possible to have a very large multiplication from a barely subcritical mass. Since there is always some neutron source present (cosmic rays or spontaneous fission), it is possible to have large neutron fluxes even from a subcritical system.

149. KINETICS

a. Something should be said of the kinetics of a neutron chain reaction. That is: At what rate does the neutron density or fission rate build up or decrease in a given medium?

b. Actually, this is a highly complex problem especially if k is approximately one. This comes about from the five or six groups of delayed neutrons which are not given off immediately upon fission. These tend to slow down the fluctuations of the reaction.

c. If k is exactly equal to one, the fission rate, power, and neutron density will remain constant with time (except for statistical fluctuations). If k is considerably greater than one, the effects of delayed neutrons due to their relatively small numbers may be neglected. This is even more valid if times much shorter than the half life emission time of the delayed neutrons is considered.

d. Let τ be the mean generation time for neutrons. This is the mean time between the birth of one fission neutron and its fathering another neutron by causing a fission. Remember that a neutron chain reaction is a statistical process. Not all neutrons travel the same distance or for the same time before a collision, but averages may be used. All the neutrons in a generation do not start out at the same time. There is not a sudden burst of fissions at the start of a generation; the fissions occur fairly uniformly throughout the generation. Let N be the number of neutrons in the first generation and N + dN the number in the second. If k is the multiplication factor, then

$$\frac{N + dN}{N} = k$$

or $$\frac{dN}{N} = k - 1$$

and $$dN = N (k - 1).$$

The time rate of change of the number of neutrons is $\frac{dN}{dt}$; and since the time each generation requires is τ,

$$\frac{dN}{dt} = \frac{N}{\tau} (k - 1).$$

Assuming k and τ remain constant, integrate this expression to find the number of neutrons at any time, t. At t = 0, there were No neutrons.

$$\frac{dN}{N} = \frac{(k - 1)}{\tau} dt$$

$$\int_{No}^{N} \frac{dN}{N} = \frac{(k - 1)}{\tau} \int_{0}^{t} dt$$

$$\ln\left(\frac{N}{No}\right) = \frac{(k - 1)}{\tau} t$$

or, $$N = Noe^{\left(\frac{k - 1}{\tau}\right) t}$$

Since the number of fissions in such a case is directly proportional to the number of neutrons, this equation also demonstrates how energy rate or power varies with time. The term

$$\frac{\tau}{(k - 1)}$$

is sometimes called the neutron growth rate or alpha.

150. SUMMARY

a. Due to the necessity of having a fairly simple presentation, many shortcuts and oversimplifications have been made here in studying the statics (criticality) and kinetics of neutron chain reactions. However, even the best quantitative treatments have not completely solved the problem. This is partly due to the microscopic nuclear data not being as complete as desired and also to the great complexities inherent in the calculations for any given system.

b. For these reasons, the best way to obtain information on a given system is to perform macroscopic experiments on the system itself; that is, for a certain type of active material, start out with a subcritical mass of it and add more in small increments. Then, determine exactly how much of the fissionable material is required for a critical mass. This is called a critical experiment.

c. Similarly, kinetic experiments can be conducted to get information on particular systems. Even here though, the quantitative calculations are extremely important. They not only tell the range in which to perform the experiment, but also allow the necessary interpolations and extrapolations to be made in going from one system to another. This greatly reduces the number of necessary experiments.

CHAPTER 8

HEALTH PHYSICS

151. INTRODUCTION

An important problem confronting personnel working with radioactive materials is the avoidance of personal harm from the adverse biological effects of nuclear radiations. Concern exists not only for the danger of illness and possible death, but also for the occurrence of undesirable mutations among the offspring of radiation victims. The following discussion will briefly review the characteristics of various types of radiation, then will describe the basic components of the human body, specific effects of radiation on these components, symptoms and treatment of radiation overexposure, and lastly will describe various means of reducing and controlling radiation intensity.

152. PARTICLES AND THEIR RANGE

a. Alpha particles are positively charged helium nuclei. They lose energy rapidly in producing dense ionization and are consequently short-ranged. This range for most alpha particles is less than 10 centimeters in air and less than 100 microns in animal tissue. Alpha emitters, when permitted to become lodged within the human body, are serious health hazards; externally, however, inability of the alphas to penetrate the dead layer of skin renders them virtually harmless, assuming the dead skin layer is unbroken.

b. Beta particles are high-speed electrons emitted from a nucleus. They produce relatively sparse ionization and have proportionately greater range in comparison with alpha particles. This range is from several meters in air to about three centimeters in animal tissue. A possible health hazard exists from external beta emitters, since their ability to penetrate body tissue is significant; beta emitters lodged within the human body are also hazardous because essentially all their energy is absorbed by the body through ionization.

c. Neutrons are neutral particles with low probability for direct ionization of matter. These particles, nevertheless, present a health hazard due to secondary ionization by the products of neutron interaction with matter. As neutrons pass through animal tissue, their collisions with nuclei cause protons or alpha particles to be ejected; these particles then produce direct ionization.

d. Gamma rays are electromagnetic radiations with neither charge nor mass. They lose energy primarily by Compton scattering and the photoelectric effect in passing through animal tissue. Gamma emitters external to the body present a definite danger due to their great penetrating ability. Remarks in this section concerning gamma radiation apply also to X-radiation.

e. Protons are positively charged hydrogen nuclei. Their behavior is similar to that exhibited by alpha particles due to charge and mass similarities.

f. Relative Ionization and Range. The relative ionization density and range of the respective radiations are presented in table 7.

Table 7. Relative Ionization

Particle	Relative Ionization	Range in Air	Range in Tissue
Gamma	1	Finite	Finite
Beta	100	3 to 7 meters	Less than 3 centimeters
Alpha	10,000	3 to 10 centimeters	0.01 to 0.10 centimeters
Neutron	0	100's of meters	10 centimeters
Proton	1,000	--	--

The gamma radiation range in air and tissue is listed as finite. Since gamma attenuation is an exponential function, absolute numerical range limitations can not be specifically assigned.

g. Mechanisms of Radiation Exposure. Personnel employed in the handling of radioactive substances must recognize the two basic mechanisms of radiation exposure: first, there may be radiation external to the body directly from a source, contamination outside the source container, or contamination on the person or clothing of the worker; second, there may be internal radiation from material collected through inhalation, ingestion, or absorption through the skin. Unnecessary exposure to any type of radiation is to be avoided.

153. THE HUMAN BODY

a. The human body is composed of the following components, here arranged in order of increasing subdivision: systems, organs, tissue, and cells. An example of this arrangement is: the respiratory system, lungs, lung tissue, and cells of the lung tissue. A specific type of tissue may occur in many different organs. Also, each specific type of tissue is composed of cells peculiar to that tissue.

b. Cell response determines radiation effects on a given tissue, which subsequently determines effects on the organ and system concerned. For example, radiation damage to the cells of the stomach or intestine could result in nausea or vomiting. Symptoms are visible effects occurring due to malfunction of a system and directly reflect cellular damage.

154. CELL COMPOSITION AND RESPONSE TO RADIATION

a. Composition and Function. All cells with exception of the red cells in the blood, have the following common components: cell membrane, cytoplasm, nuclear membrane, and nucleus.

(1) The cell membrane completely encloses the cell and is semipermeable to permit passage of nutritional materials into the cell and passage of waste materials out of the cell. Permeability of the membrane may be either impaired or improved by the influence of radiation.

(2) The cytoplasm comprises the bulk of the cell and is composed of water, fats, proteins, etc. Also contained in the cytoplasm are biological catalysts called enzymes, which control the chemical changes by which energy is provided for body processes and activities. Normally, this process, called metabolism, is not significantly affected by radiation.

(3) The nuclear membrane surrounds the nucleus within the cell and is similar to the cell membrane. Its composition and functions are presumably very similar to those of the cell membrane.

(4) The nucleus is the governing body of the cell and is the part most sensitive to radiation. It is composed almost entirely of protein. Radiation effects on the nucleus are determined by the relative activity of the nucleus at the time of irradiation; that is, the stage achieved by the nucleus in the process of division. The cells most susceptible to radiation damage then are those which divide most rapidly. On this basis, radiosensitivity can be classified as follows: most sensitive - bone marrow, lymph glands, lining of mouth and intestines, hair follicles, and skin; moderately sensitive - liver and

kidney tissue; least sensitive - nerve, brain, and muscle tissue.

b. Response to Radiation. Irradiation of a cell can cause damage to components of the nucleus-controlling characteristics of daughter cells, resulting in the production of so-called mutations. The probability that such mutations may ultimately be manifested in the appearance of offspring with characteristics radically different from those of the parents is only about one in 10,000 for maximum sublethal radiation doses. This probability is not significantly different from the probability for natural occurrence of mutations. Since greater mutation probabilities would involve lethal radiation doses, they need not be considered.

155. UNITS

a. Biological definitions for radiation units are unique in the sense that biological effects are determined by the absorption of energy in tissue and not simply by the amount of energy passing through the tissue. For example, a beam of high-energy gamma rays is quite penetrating and may produce fewer biological effects per unit of tissue than less penetrating, low-energy gamma rays with the same total energy flux.

b. The roentgen (r) is defined as that amount of X- or gamma-radiation required to produce by ionization 1 electrostatic unit of charge in 1 cubic centimeter of dry air at standard temperature and pressure. Combining this definition with certain experimental observations permits the establishment of more useful units. One roentgen is equivalent to:

(1) 2.08×10^9 ion pairs per cubic centimeter of air at standard temperature and pressure, or

(2) 1.6×10^{12} ion pairs per gram of air at standard temperature and pressure, or

(3) 6.8×10^4 Mev per cubic centimeter of air at standard temperature and pressure, or

(4) 5.2×10^7 Mev per gram of air at standard temperature and pressure, or

(5) 83 ergs per gram of air at standard temperature and pressure.

The biological effects of high-energy radiation are much more profound than might be expected from the total energy absorbed. The absorption of 1000 roentgens of radiation by the whole body would almost certainly be fatal; however, the total temperature rise due to the absorbed energy would be only 0.002° C. and only about 2 atoms out of 10^8 would be ionized.

c. The roentgen, applying only to X- or gamma-radiation, can be logically extended to provide appropriate units for the particulate radiations. The roentgen equivalent physical (rep) is that amount of ionizing radiation required to produce 1.6×10^{12} ion pairs or 93 ergs of heat energy per gram of tissue. It is to be noted that the production by X- or gamma-radiation of 1.6×10^{12} ion pairs in a gram of air at standard temperature and pressure results in heat liberation of 83 ergs from the loss of 32.5 ev per ion pair formed. The energy loss in tissue is 35.0 ev per ion pair formed, producing heat liberation of 93 ergs per 1.6×10^{12} ion pairs. The biological effect of radiation is measured by the roentgen equivalent man (rem), which is that amount of radiation of any kind which will produce in man an effect equivalent to that produced by the absorption of one roentgen of X- or gamma-radiation. Application of this unit may be complicated somewhat by slight differences among radiations in relative effectiveness, depending upon the particular effect chosen for observation.

d. Relative biological efficiency (Rbe) for our purposes is the ratio for a given amount of a specific radiation of the number of roentgen equivalent men to the number of roentgen equivalent physicals. We may consider this ratio a dimensionless number to facilitate comparisons among different types of radiations. The Rbe for some of the common radiations is as follows:

Alpha	-	20
Beta	-	1 to 2
Gamma	-	1
Neutrons (slow)	-	2
Neutrons (fast)		10
Protons		5

e. Relationship of Radiation Units. Table 8 gives the relationships among r, rep, and rem for several types of radiation. It should be remembered that a rep of one type of radiation is equivalent in energy loss to a rep of any other type of radiation. Likewise, a rem of one type of radiation is equivalent in biological effect to a rem of any other type of radiation.

Table 8. Radiation Relationships

Radiation	r	rep	rem
X-ray	1	1	1
Gamma	1	1	1
Beta	Not defined	1	1
Proton	Not defined	1	5
Alpha	Not defined	1	20
Neutrons (fast)	Not defined	1	10
Neutrons (slow)	Not defined	1	2

156. RADIATION DOSES AND EFFECTS

a. A radiation dose is the total quantity of radiation absorbed by an organism during a single radiation experience. Since the roentgen, upon which the other units are based, is an amount of energy absorption per unit volume or mass, the quantity of tissue affected must be specified to permit a quantitative measure of the dose concerned. If one finger receives 1000 r, the systemic effect will be much less severe than that which would be sustained from a whole-body absorption of 1000 r. The amounts of ionization per gram of exposed tissue are identical, but the respective doses are obviously quite different due to the unequal quantities of tissue exposed.

b. Dose rate is the dose received per unit time.

c. Dosage is the summation of doses received over a period of time. For example, a given operation may result in the operator receiving a whole-body dose of 0.01 r. If the operation is performed 15 times a day, the daily dosage will be 0.15 r; and the dosage per 5-day work week will be 0.75 r.

d. Measurement. Biological injury from radiation exposure depends upon the amount of tissue ionized; hence, a good survey meter should indicate a response proportional to the tissue ionization produced. Ionization chamber instruments can be designed to give the proper response over a wide energy range, and quantitative surveys must, in general, be made with such instruments. Geiger-Mueller counters respond to the amount rather than ionizing power of any incident radiation. For example, 100 beta particles of 0.15 Mev energy from C-14 would produce the same Geiger-Mueller counterresponse as 100 beta particles of 3.5 Mev energy from K-42 despite the fact that the latter have about 25 times more ionizing power than the former. Unless specially calibrated, a Geiger-Mueller counter should be considered a sensitive radiation detector rather than an instrument capable of quantitative measurement.

e. Effects. In establishing limits for exposure to radiation, situations which have produced known injuries must be evaluated. Many cases of radiation injury have occurred unfortunately, but equally unfortunate is that in most of these cases no accurate tissue dose data were obtained. Therefore, any figures for permissible exposures are subject to modification as more information is obtained. The permissible whole-body radiation dose is 0.3 r per week in the United States. Higher exposures are permitted under unusual circumstances, provided the whole-body dose for any 2-week period does not exceed 0.6 r. Future military operations in time of war might, of course, require exposure to doses considerably in excess of this limit. There are undoubtedly very wide variations in individual sensitivity to radiation. Unfortunately, little quantitative information is available.

f. An overexposure to radiation is usually first indicated by a drop in the white cell count of the blood. This drop is proportional to the dose received. The white count is a function of general body condition, of course, and only a persistent low count or a pronounced low count following known radiation exposure should be viewed with great concern. A drop in the red cell count in the blood may also occur. Unfortunately, this effect is somewhat latent and may not be detected for several days even after severe overexposure.

g. Effects of radiation on skin tissue are manifested in such symptoms as ulcers of the mouth, throat, and intestines. These hemorrhage in time and cause bleeding gums, vomiting, bloody diarrhea, etc. Later, pinpoint and blotchy hemorrhages appear in the skin, and loss of hair occurs.

h. The effect of radiation exposures slightly above tolerance at intervals over a considerable length of time can be various anemias and blood damage, bone damage, kidney damage, liver damage, and tumor formations. These effects will not be discussed extensively in this text.

i. External alpha-particle bombardment has no biological effect because most of the particles are absorbed in the dead layers of skin. Beta particles, however, can penetrate the dead layer of skin. Very energetic beta particles can penetrate up to 3 centimeters of tissue. The effects of beta overexposure are almost entirely surface in nature and appear as burns whose severity is determined by the extent of the overexposure. Neutrons can penetrate up to 10 centimeters of tissue. Few human organs therefore are safe from neutron damage. It has been pointed out previously that neutrons produce alpha particles or protons (primarily scattered photons); hence, the effects will correspond to those associated with internal alpha exposure, which is very dangerous. Strict isolation of the effects due to neutron exposure is difficult because large neutron doses are commonly accompanied by large doses of gamma radiation and the biological effects are intermingled. In addition to the damage from primary ionization, a very intense neutron exposure can produce radioactive isotopes in the body.

j. Tolerances. It is almost universally accepted in the United States that 0.3 r per week is the maximum whole-body dose capable of being indefinitely sustained without harmful effects. Any revision of this limit would probably be downward. A dose of 0.0001 r per day from cosmic radiation alone is experienced at sea level. This dose increases to 0.3 r per day at 40,000 feet, the increase being due to low radiation attenuation by the rarefied atmosphere at high altitudes.

k. The 5-percent lethal dose (LD-5) is that dose at which essentially 5 percent of those exposed will be fatalities within a short period of time. The accepted figure for this value is 150 r received in a short time interval. The 50-percent lethal dose (LD-50) is considered to be 450 r received in a short time interval. The 100-percent lethal dose (LD-100) is a somewhat nebulous figure since it is unlikely that any dose will definitely kill all those exposed. It is probable, however, that a dose of 600 r received in a short time interval will kill 999 out of 1000 people. The mean lethal dose is that dose at which those exposed have a survival probability of $1-1/e$ or about 63 percent. This dose for humans is probably about 380 r received in a short period of time. (Recent investigations indicate that the actual LD-50 might be 645 r with the LD-100 increased accordingly.)

l. The Los Alamos Scientific Laboratory has established the following body neutron tolerances for a 40-hour work week:

Thermal neutrons - 2000 neutrons per square centimeter per second
Slow neutrons - 1000 neutrons per square centimeter per second
Fission neutrons - 80 neutrons per square centimeter per second
Fast neutrons - 30 neutrons per square centimeter per second.

The lethal whole-body neutron dose is considered to be 10^{11} neutrons per square centimeter received within a few days.

m. Medical treatment or examination involving a single X-ray picture exposes the body to doses of 0.1 r to 3 r. Fluoroscopic examinations expose the body to doses up to 30 r.

n. Military tolerances are variable. Present Strategic Air Command policy permits aircrews to receive 75 r for a single mission or 25 r per mission for 8 missions, provided the exposures are at least 1 week apart. Army and Navy tolerances are individually established at high command levels.

o. Uranium handling tolerances are based primarily on beta emission from the uranium daughter products. The natural uranium tolerance for direct hand contact is 6 hours per week. The tolerance is increased to 12 hours per week by the use of gloves 1 millimeter thick. The handling tolerance for uranium enriched to nearly 100 percent uranium-235 is about 16 hours per week. The increased tolerance compared to the natural uranium tolerance is attributable to the lesser beta activity of the daughter products.

p. The barehanded tolerance for plutonium is 1.5 hours per week. With thin gloves, the tolerance rises to 5 hours per week. Application of a metallic coating to the plutonium greatly decreases the beta radiation and raises the tolerance to 20 or 30 hours per week.

q. One curie of polonium emits gamma radiation of about 65 milliroentgens per hour at a distance of 1 centimeter. The artifically produced polonium is normally processed to remove impurities, particularly oxygen, and thereby to lower the neutron activity to less than 100 neutrons per second per curie. If exposed to air, the neutron activity of the polonium may rise to as much as 2800 neutrons per second per curie. When combined with beryllium, the mixture emits gamma radiation of about 1.1 r per hour at a distance of 1 centimeter.

157. INTERNAL RADIATION HAZARDS

a. Many factors influence the hazard presented by radioactive materials which become lodged within the body. Such factors as activity (half life), types of radiation emitted, location in the body, and duration of internal exposure, are typical.

b. Radioactive materials may enter the body by inhalation, ingestion, or directly through breaks in the skin. Once within the body, the chemical nature of the substance determines its disposition. Some materials are rapidly eliminated in the body wastes. Others, such as radium and plutonium, are bone seekers and are, therefore, very difficult to dislodge. Uranium lodges in such organs as the kidneys. Tritium, being a hydrogen isotope, becomes distributed throughout the body.

c. Short isotopic half lives indicate high radioactivity. In general, then, materials with short half lives present internal hazards proportionately greater per unit mass than those presented by materials with long half lives.

d. Because the bodily processes include complex and extensive chemical activities, every substance entering the body has a definite probability of being eliminated. This probability is reflected in the quantity called metabolic half life, which is the length of time necessary for elimination from the body of one-half of any contained radioactive substance. The elimination process is an exponential one (i. e., amount of material in body varies exponentially with time).

e. A radioactive substance within the body is dissipated by two means: radioactive decay and physiological elimination. These processes have discrete half lives. Their combined effect is represented in a new value called biological half life, which is less than that of either eliminative process. The following mathematical expressions apply:

Let $t_{1/2}\,(\text{rad})$ = radiological half life

$t_{1/2}\,(\text{met})$ = metabolic half life

$t_{1/2}\,(\text{biol})$ = biological half life

$$\lambda\,(\text{rad}) = \frac{0.693}{t_{1/2}\,(\text{rad})}$$

$$\lambda\,(\text{met}) = \frac{0.693}{t_{1/2}\,(\text{met})}$$

$$\lambda\,(\text{biol}) = \frac{0.693}{t_{1/2}\,(\text{biol})} \quad \text{where the } \lambda\text{'s are decay constants}$$

$$\frac{1}{t_{1/2}\,(\text{biol})} = \frac{1}{t_{1/2}\,(\text{rad})} + \frac{1}{t_{1/2}\,(\text{met})}.$$

f. While alpha particle emitters external to the body are essentially harmless, internally their intense tissue ionization is very hazardous. Beta particle emitters constitute roughly the same hazard whether situated externally or internally. Tissue ionization from contained gamma emitters is very sparse; and, therefore, it is seldom felt necessary to consider gamma emission in the calculation of tolerances. General levels of maximum permissible concentration (MPC) considered safe for any radioactive isotope, except strontium-90, plutonium-239, or radium-226, are as follows:

Media	Beta-Gamma Emitter	Alpha Emitter
Air	2.22×10^3 d/m/m^3	11.1 d/m/m^3
Water	222 d/m/l	222 d/m/l

d/m/m^3: disintegrations per minute per cubic meter
d/m/l: disintegrations per minute per liter.

Specific isotopic tolerances are presented in table 8.

Table 8. Maximum Permissible Concentrations of Various Radioactive Isotopes in Water and Air[1]

	Air - d/m/m^3	Water - d/m/l
Cobalt-60	2.2×10^6	44×10^6
Tritium	44.4×10^6	444×10^6
Plutonium-239	4.44	3.3×10^3
Polonium	444 (soluble) 155 (insoluble)	67×10^3 67×10^3
Tuballoy	37.7	155×10^3
Oralloy	3.3×10^3 (soluble) 66 (insoluble)	3.55×10^3 3.55×10^3

g. The tolerance for ingested radioactive material is a function of the quantity of the material which will be absorbed through the walls of the gastrointestinal tract. This quantity depends upon the material, general body condition at the time of exposure, and many other factors.

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[1] It should be noted in comparing permissible concentrations that they are on an activity (disintegration per unit time) basis and not a mass basis.

It is necessary in establishing the tolerance to make a generous allowance for indeterminate variables.

h. Figures for maximum permissible air contamination are based upon the assumption that 75 percent of the material inhaled will be absorbed by tissues of the upper respiratory tract and only 25 percent will reach the lungs. This distribution would tend to minimize the quantity of material reaching the blood stream, but the material absorbed in the upper respiratory tract would, of course, badly damage those tissues.

i. Tritium, an isotope of hydrogen, has an atomic mass of three and is a low-energy beta emitter. It may enter the body through inhalation or absorption through the skin. It is thought that this material becomes distributed throughout the body. It has a biological half life of approximately 12 days, which can be reduced considerably by raising the fluid intake, and thereby increasing the volume eliminated.

158. TREATMENT OF RADIATION SICKNESS

a. Treatment of radiation sickness can not achieve a cure in the same sense that treatment of a bacterial or virus infection can; that is, the cause is not removed. Treatment of the illness can be best directed toward minimizing the deleterious effects of dangerous exposure to radiation.

b. Whole-body transfusions are given to counteract the extensive blood damage from radiation. Antibiotics are administered to bolster body resistance, lowered by white blood cell destruction, to secondary infection. The victim may be fed intravenously to circumvent inability to eat or loss of appetite due to nausea, vomiting, ulcers in the mouth and throat, etc.

c. Much research has been devoted to the problem of discovering a chemical treatment to prevent radiation sickness. Although some encouraging results have been obtained, the problem is still far from solution.

159. PERSONAL PROTECTIVE MEASURES

a. Personal Problems. Wide dissemination of correct information concerning the dangers of radiation would eliminate much of the needless worry due to misapprehension among the general public. Such worries as the supposed danger of permanent sterility from overexposure and possible high incidence of undesirable mutations among the progeny of irradiated parents are typical.

b. Protective Measures. To limit external exposure, any one or all of the following measures may be taken:

(1) Remove the source of contamination. If the source is not being used, take it to a segregated storage place. Removal of contamination is much easier if proper precautions, such as covering the area with Kraft paper or painting the surface with "strippable" plastic paint, have been taken before the material becomes dispersed. Decontaminating an unprotected surface is primarily an abrasive process, scrubbing with a detergent and water, "hosing down" with high-pressure water or steam, using a complexing agent such as citric acid, or removing the surface with acid or by sandblasting. Each worker should be given protective clothing, which provides enough coverage to protect the worker as well as his personal clothing, and which can be washed in a laundry equipped to handle contaminated clothing and dispose of the contaminated wash water.

(2) Limit the amount of time spent in a radiation area. Determine the rate of exposure, and limit the amount of time the worker spends in that area to that which will give him only his permissible exposure. Each worker should be given personnel monitoring equipment to record the exposure which he will receive.

(3) Reduce the rate of exposure. Interposing shielding between the source and the worker or moving the worker farther from the source will reduce the rate of exposure to the worker. Lucite or glass can be used for beta shielding. Paraffin and water are acceptable for fast neutron attenuation. The internal exposure can be controlled only by preventing the entry of radioactive materials into the body. Respiratory protection for short periods in low concentrations of airborne contamination may be provided by respirators which filter the air to the mouth and nose. For higher concentrations (50 times the MPC), supplied air masks are recommended. Nose swipes taken at the end of a working period may be used as indicators of inhaled contamination. Eating and smoking should not be permitted in contaminated areas. Workers should be properly indoctrinated to use hand counters, to request surveys often when handling radioactive materials, and to report immediately all injuries where the skin is broken in order that any contamination may be removed with minimum absorption.

(4) The amount of material which has reached the interior of the body can be estimated by the quantity found in the body fluids. The urine is the most available body fluid. Whenever an internal

exposure is suspected, a urine specimen should be requested and analyzed as soon as possible. Radium, for example, quickly becomes fixed in the bone and can then only be detected by taking breath samples and counting them in a Radon Breath Counter.

c. Materials which are contaminated with short-lived isotopes can be stored until normal decay makes possible their disposal through usual channels. A segregated burying pit, plainly marked and surrounded by a high, strong fence, is used for disposal of waste contaminated with long-lived radioactive isotopes. All contaminated waste should be packaged in sealed containers and labelled for hauling to the dump. The vehicle used for hauling the waste should be of such construction that it can be decontaminated easily.

d. Natural radiation sources should be leak-tested whenever dropped, or when deterioration of the container is suspected, or at least once every 6 months. Polonium sources are especially dangerous because of the marked tendency of polonium to escape and spread.

CHAPTER 9
NUCLEAR POWER

Introduction

The material contained in chapters 1 through 8 and in Appendices I through VIII is basic principles of nuclear physics prepared by the Special Weapons Training Group, Field Command, Armed Forces Special Weapons Project. It does not include the application of these principles to either nuclear weapons or to nuclear power and propulsion, although, as stated in the Foreword, it is slanted toward the particular objective of supplying background information to students in Special Weapons training. Nuclear weapons applications are being covered in two books titled Guided Missiles and Nuclear Weapons Orientation and Guided Missiles and Nuclear Weapons.

This chapter has been added here to give an orientation in the applications of these principles to the very important area of nuclear power, particularly as it applies to naval power plants and the propulsion of naval vessels.

SECTION I. REACTOR PRINCIPLES

Previous chapters presented a discussion of the atom, its structure, and the constituent particles and their behavior. We have seen how energy is released when the atom is split ($E = mc^2$). The Einstein formula shows the equivalence of mass and energy. All machines used by man are a means of doing work. Our concern is with machines that will convert heat into motion. Now we have entered into the era where the infinitesimal atom is producing heat for the propulsion of ships.

For naval propulsion, atomic energy must be capable of being controlled if it is to be used to drive engines. The energy must be produced in small enough quantities at any given time so as not to become harmful to operating personnel. If the harmful effects of nuclear energy can be guarded against and the chain reaction controlled so that it does not run away and become explosive, then the energy encompassed in the atom can be harnessed for ship propulsion.

160. COMPARISON OF COMBUSTION AND FISSION

In the familiar chemical reaction of combustion, mass is changed into energy. In an ordinary combustion process, there is a rearrangement in the atoms of the fuel and air molecules to form the molecules of the combustion products. During the burning process an insignificant amount of the mass is converted to energy. For example, when one pound of coal is burned, 14,000 Btu are produced--less than one billionth of a pound of coal is converted to energy in the production of heat. However, in a fission reaction, when the nuclei of certain atoms are split, approximately $\frac{1}{1090}$ of their mass is converted to heat energy.[1] The fissioning elements change into different elements, a phenomenon which does not occur in a chemical reaction such as combustion.

In a previous chapter it was said that fission occurs when the nucleus of a U^{235} atom is struck by a neutron. This upsets the internal balance of forces between the neutrons and protons in the U^{235} nucleus, and the nucleus splits into two lighter nuclei; at the same time, energy is released. In each fission, two or three neutrons are emitted; and if one of these neutrons is captured by another fissionable nucleus, the fission chain reaction continues with the production of energy. The device in which the nuclear fission chain is initiated, maintained, and controlled so that the energy may be released at a specified rate is called a nuclear reactor.[2] Reactors will be discussed later in this chapter.

At the present time there are three radioactive materials whose properties are suitable for sustaining a neutron chain reaction. These readily fissionable (fuel) materials are the isotopes U^{233}, U^{235}, and Pu^{239}. These three nuclear fuels are capable of causing other atoms to fission--that is, they can convert fertile materials into fissionable materials. A fertile material is defined as any substance which cannot itself sustain a chain reaction, but which can be placed in a reactor and converted into fissionable material.

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[1] A pound of uranium metal just slightly larger than a one-inch cube can produce the same amount of energy as 3 million pounds of coal. This energy could light the city of Chicago for a full day, or the average home for 9000 years.

[2] Some texts use the term "atomic pile." This term originated from the fact that the first successful reactor was constructed by piling layers of graphite (some containing uranium) one upon another.

The isotope U^{233} is made from thorium 232 (Th^{232}) by bombarding the Th^{232} nuclei with neutrons:

$$ {}_{90}Th^{232} + {}_{o}n^{1} \longrightarrow {}_{90}Th^{233} \xrightarrow[23\ min]{\beta-} {}_{91}Pa^{233} \xrightarrow[27.4\ d]{\beta-} {}_{92}U^{233} $$

Thus, when thorium 232 is exposed to neutron bombardment, thorium 233, a negative beta emitter with a half life of 23 minutes decays to protactinum 233 (Pa^{233}) which in turn decays (half life 27.4 days) to form U^{233}.

The source of U^{235} is in natural uranium of which it constitutes about 0.7 percent, while the other 99.3 percent consists mainly of U^{238}. Uranium 235 is separated by means of a complex gaseous diffusion process where it is converted into a usable form of metal or liquid.

Plutonium 239 (Pu^{239}) is made from naturally occurring U^{238} by adding a neutron:

$$ {}_{92}U^{238} + {}_{o}n^{1} \longrightarrow {}_{92}U^{239} \xrightarrow[23\ min]{\beta-} {}_{93}Np^{239} \xrightarrow[2.3\ d]{\beta-} {}_{94}Pu^{239} $$

Thus, when U^{238} is exposed to neutron bombardment, uranium 239, a negative beta emitter with a half life of 23 minutes decays to neptunium (Np^{239}) also a negative beta emitter (with a half life of 2.3 days). The excited nucleus emits alpha and beta particles and gamma radiations and finally becomes Pu^{239}, a long-lived alpha emitter.[3]

161. CHAIN REACTIONS

There are two results of a fission reaction that are of importance to this discussion. The first is the large amount of energy released. The greater part of this energy appears as kinetic energy of the fragments and neutrons that result from a fission reaction. Fission fragments and neutrons collide with surrounding nuclei and set them in motion. These other nuclei, in turn, collide with further nuclei, etc. It is through these numerous collisions that the energy of the fission fragments is spread. These fission fragments are stopped by the surrounding materials (fuel, structural parts, etc.) and the kinetic energy is released in the form of heat.

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[3] For further information about nuclear fuels see Sourcebook on Atomic Energy by Glasstone, S., New York, D. Van Nostrand Co., Inc., 1950.

The second result of a fission reaction is that two to three neutrons are released. In order for a fission reaction to continue, the multiplication factor, k, must be at least equal to unity (one). The multiplication factor is the ratio of the number of neutrons in any one generation to the number of corresponding neutrons of the immediately preceding generation. If k is equal to or slightly greater than unity, a chain reaction can take place. If k is less than unity, the chain reaction cannot continue and will ultimately die down. Since some of the neutrons produced in a reactor may be lost through leakage or absorption, fission reactions must produce more than one neutron per fission. Whether a reactor becomes subcritical, critical, or supercritical depends upon whether the k factor is less than, equal to, or greater than unity. Critical is the term used to describe the condition of a nuclear reactor in which a fission chain reaction is being maintained at a constant rate. A reactor in which the rate of fissioning is increasing is said to be supercritical, and one in which the rate is decreasing (i.e., there is no chain reaction) is termed subcritical.

It was previously stated that there are two to three neutrons produced during each fission. In order for a self sustaining reaction to take place, at least one neutron must enter a nucleus to initiate a fission reaction. If a reactor becomes supercritical, then neutrons must be removed. Removal of neutrons from the uranium is accomplished by means of control rods which may be moved in or out of the reactor core (fig. 70). A control rod regulates the reaction rate in a nuclear reactor by changing the effective multiplication factor (k_{eff}). Control rods, which absorb neutrons, are usually made of cadmium or boron (in the form of boron steel). Sometimes absorbing control rods are made of fertile material to utilize the neutrons absorbed in control.

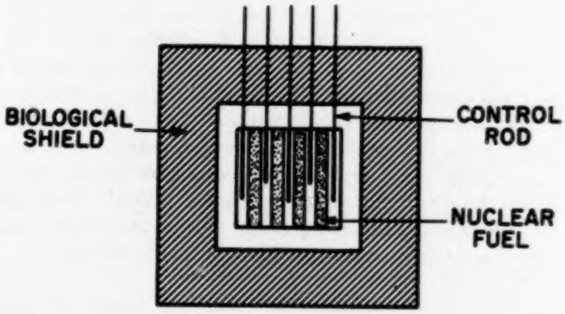

Figure 70. Schematic Illustration Showing Position of Control Rods

When a reactor is to be started from a shutdown condition, the control rods are pulled out slowly until k is greater than unity.

162. REACTOR DEVELOPMENT

Within the brief span of ten years, nuclear reactors have proved themselves an indispensable research tool in a variety of fields. Up until 1953, all reactors in the United States were owned by the Government and were operating on Government-owned sites. Within recent years, however, a considerable number of private research institutions and universities have planned, built, and operated research reactors on their own sites, with active encouragement from the U. S. Atomic Energy Commission.

Nuclear reactors may be classified in several different ways, depending on the type and arrangement of fuel, moderator, coolant, and on the speed of the neutrons sustaining the fission reaction. Materials used to reduce the neutron energy, known as moderators, are primarily graphite, light water, and heavy water (deuterium oxide). Active fuel materials may be natural uranium; enriched uranium, in which the U^{235} fraction has been increased; plutonium (Pu^{239}); or uranium (U^{233}) resulting from fission of thorium (Th^{232}). The last two are artificial reactor-produced elements.

a. Classification According to Fuel Arrangement

The arrangement of moderator and fuel provides a basis of classification. In a heterogeneous or solid-fuel reactor the fuel is fixed in a regular pattern (lattice) within the moderator. In a homogeneous reactor the fuel and moderator are intimately mixed in the form of a solution, aqueous or metallic.

Reactors operated above minute power levels must use some form of cooling to remove the heat produced. Light-water, heavy-water, or air coolants are generally used; either convection or forced circulation is employed.

b. Classification According to Neutron Energy

Reactors are further classified according to the speed or energy of the neutrons that cause fission. A thermal reactor (slow neutron) is one in which fission is induced primarily by neutrons of such energy that they are in substantial thermal equilibrium with the material of the core. The core of a nuclear reactor may be considered as the region containing the fissionable material, the body of fuel, or moderator and fuel. It does not include the fuel outside the active section in a circulating reactor. In a heterogeneous reactor, it is the region containing the fuel-bearing cells. A representative energy for thermal neutrons often is taken as 0.025 electron volts (ev).[4] Reactors in which most of the fissions are caused by neutrons which have energies above the thermal range are called intermediate reactors. From 0.5 to 100,000 ev may be taken roughly as the energy range of neutrons which induce fission in the intermediate reactors. A fast reactor is one in which there is little moderation and fission is induced primarily by fast neutrons that have lost relatively little of the energy with which they were released. About 100,000 ev is regarded as the minimum value of mean energy of neutrons inducing fission for a fast reactor, with 1/2 to 1/3 Mev more common.

c. Classification According to Use

Finally, reactors may be classified according to their purpose. A power reactor is one which is capable of providing useful mechanical power. This is done by generating energy in the form of heat conveyed at a temperature high enough for reasonably efficient conversion to mechanical work. Power breeders are nuclear reactors designed to produce both useful power and fissionable fuel. A production reactor is designed primarily for large-scale manufacture of fissionable materials by conversion of nonfissionable (fertile) materials. Research reactors are built primarily to supply neutrons, other particles, and gamma radiation for physical research and radioisotope manufacture.

163. REACTOR COMPONENTS

Nuclear-reactor design is in its infancy. However, the component parts of all currently operating reactors have similar units. Components[5] of current reactors are listed in table 1.

a. Fuel Elements

It has previously been stated that the three radioactive materails whose properties are suitable for sustaining a nuclear chain

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[4] The ev is a unit of energy equivalent to the amount of energy gained by an electron in passing through a potential difference of one volt. Larger multiple units of the ev are frequently used, viz: Kev for thousand or kilo electron volts; Mev for million electron volts and Bev for billion electron volts.

[5] For a thorough discussion see Principles of Nuclear Reactor Engineering, Glasstone, S., New York, D. Van Nostrand Co., Inc., 1955.

Table 1. Reactor Components

Component	Material	Function
1. Nuclear fuel elements	U^{233}, U^{235}, Pu^{239}	Sustain the fission reaction
2. Moderator	Carbon (C), heavy water (D_2O), light water (H_2O), and beryllium (Be)	Reduce the energy of the fast neutrons to thermal neutrons
3. Coolant	Air, H_2O, D_2O, sodium (Na), sodium-potassium (Na-K), bismuth (Bi), and gas (CO_2)	Remove heat
4. Control rods	Cadmium (Cd), boron (B), and hafnium (Hf)	Control the neutron production rate
5. Reflectors	Same as for moderator	Minimize neutron leakage
6. Shielding	Concrete, steel and water, lead, and polyethylene	Protect operating personnel from radiation
7. Structural	Aluminum (Al), zirconium (Zr), steel, and stainless steel	Physical support and containment of the fuel elements

reaction are U^{233}, U^{235}, and Pu^{239}. Uranium 233 and plutonium 239 are actually made in a reactor by neutron bombardment.

Uranium production in the atomic energy program is a long, complex chain of manufacturing processes that starts with uranium-bearing ores and ends with cylindrical rods of the purest uranium metal ever prepared in quantity. Chemical impurities that would capture neutrons are intolerable. After the processes of ore treatment, purification, and reduction to metal, which are difficult enough, comes the problem of jacketing the uranium slugs to protect the metal from corrosion. Uranium possesses great affinity for oxygen; hence to avoid trouble and prevent loss due to oxidation, special precautions must be taken during processing. All melting and casting is done in a vacuum. Fabrication work, when possible, is done at low temperatures to avoid rapid oxidation. Other precautions involve working the metal in an inert atmosphere, or rapid manipulations or jacketing of the metal to reduce the oxidation period.

Uranium 235 actually starts out as an orange-colored powder--a highly refined but impure form of the uranium extracted from the natural ore. To make this powder into a gaseous feed for the process, the powder is combined with the highly corrosive element fluorine, and becomes a gas--uranium hexafluoride (one atom of uranium and six atoms of fluorine). This gas is pumped through miles of piping separated at intervals by porous membranes called barriers. In these barriers there are billions of holes, each less than two-millionths of an inch in diameter.

All of the uranium atoms can pass through the tiny holes in the barriers with room to spare, so they cannot be separated by screening or filtering. But the U^{235} atoms tend to go through first because they weigh less and move just a little faster. Only a few of the lighter atoms get through the holes ahead of the others, and this slightly enriched gas is immediately pumped onto the next stage for further processing. The rest is sent back to start all over again.

The corrosive uranium hexafluoride gas actually recirculates many thousands of times through the system before it becomes rich enough in U^{235} atoms. It is then converted into a usable form--metal or liquid--for atomic energy operations.

Plutonium 239 starts as slugs of U^{238} which have been exposed to neutron bombardment in a reactor for a considerable length of time. When the slugs are removed, the radioactivity at this point is so intense that the slugs have a blue-white glow.

Inside the aluminum jacket, the irradiated slug is no longer uranium alone. It is more uranium than anything else, but it also contains small amounts of neptunium and plutonium and somewhat larger quantities of other impurities--radioactive forms of more than forty elements, such as barium, iodine, cerium, etc.

Extracting plutonium from this slug is very difficult. The first step is comparatively easy, though somewhat complicated by the fact that the chemist must do everything by remote control if he wishes to live to run another batch. The jacketed uranium slugs are dumped into a tank, and a solution is added which dissolves the jacket but not the uranium. After the solution has done its work, it is drained off and the uranium, along with all its impurities, is dissolved with another reagent. This solution then goes to a separation plant where the plutonium is precipitated out in final form. This is the solid that can be filtered off and converted into metal by metallurgical processes.

b. Moderator

The slowing down of neutrons plays an important role in many nuclear reactors, and the material used for the purpose is called a moderator. The process of slowing down as a result of scattering the fission collisions is referred to as moderation. A good moderator is made of a material which reduces the speed of fast neutrons in a small number of collisions. Consequently, materials consisting of atoms of low mass number make the best moderators. The four moderator materials which are currently being used on operating reactors are light (ordinary) water, heavy water, beryllium, and carbon (graphite). From an economical point of view, light water is a desirable moderator because it is relatively abundant and costs so very little. Light water may be used as both moderator and coolant in some types of reactors (enriched fuel type). However, the water must be free from impurities since these not only capture neutrons but they may become radioactive as a result of neutron and gamma reactions. This presents a problem if radioactive material appears in the cooling system. One of the main disadvantages of using water as a moderator is its relatively low boiling point. Thus, in order to be used in high temperature reactors, the pressures must be high. This presents problems in the fabrication of reactor parts.

Heavy water (D_2O) makes an excellent moderator--in fact, one of the best. However, the drawback to deuterium oxide is the cost of production.

Beryllium is one of the most efficient of the solid moderator materials in current use. It is used either in metallic form or as beryllium oxide because it has low neutron cross-section properties.[6] Beryllium is the only light metal (low density) that has a high melting point, 3245° F or 1285° C.

Graphite makes a good moderator because it is an excellent conductor of heat, a desirable characteristic of any moderator. The chief disadvantages of graphite is that at high temperatures graphite reacts with oxygen, water vapor, and some metal oxides to form carbides.

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[6] Neutron cross-section implies the probability of neutron interaction with the bombarded, in this instance, beryllium nuclei. The probability of a specific nuclear reaction taking place is measured in barns: numerically a barn is equal to $10^{-24} cm^2$.

c. Reactor Coolants

The primary purpose of a reactor coolant is to heat from the reactor. In order to accomplish this task the coolant must possess good heat-transfer properties. The coolant may be either a gas or a liquid. In general, a coolant should possess the following characteristics: (1) good thermal properties, e.g., high specific heat and thermal conductivity; (2) high boiling point and low melting point; (3) low power requirement for pumping; (4) stability to heat and radiation; (5) noncorrosive to the system; (6) nonhazardous as a result of exposure to radiation; and (7) low cost. Some of the coolants used in currently operating reactors are light water, heavy water, liquid sodium, helium, dry air, carbon dioxide, lithium, and bismuth.

d. Control Rods

The power output of any reactor is directly proportional to the neutron density, i.e., the number of neutrons per unit volume. The only practical means of increasing the neutron density is by slowly pulling out the control rods until k_{eff} becomes greater than unity. A reactor is said to be subcritical if k_{eff} is less than unity. By withdrawing the control rods so that k_{eff} is greater than unity, the fission reaction causes the neutron density to increase until the desired level corresponding to the required power output is attained. The control rods are then inserted so as to make k_{eff} equal to unity, thus giving a constant power output.

There are various types of control rods that are used in operating reactors. The first of these are known as shim rods. A shim rod is a control rod that is used for making occasional coarse adjustments in the reactivity[7] of a nuclear reactor. The shim rod moves more slowly than a regulating rod and, singly or as one of a group, is capable of making a greater total change in the reactivity. A shim rod commonly is positioned so that the reactor will be just critical (reactivity = 0, $k_{eff} = 1$) when the regulating rod is near the

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[7] Reactivity is an indication of the condition of a reactor with respect to criticality. Negative values indicate subcriticality, zero indicates critical, and positive values indicate supercriticality.
$$\text{Reactivity} = \frac{k_{eff} - 1}{k_{eff}}$$

middle of its range of travel. Shim rods are used to bring a reactor approximately to the desired power level when the system is started up. When the desired power level of the reactor is approached, the shim rods are repositioned so as to reduce k_{eff} almost to unity.

Another set of control rods are the regulating rods which are used for rapid, fine adjustment of the reactivity of a reactor. The regulating rods are capable of moving much more rapidly than the shim rods but make a smaller change in a reactor's reactivity. Regulating rods are used to maintain the desired power output of a reactor.

A third set of control rods are known as safety rods. These rods are capable of shutting down a reactor very quickly in case of failure of the ordinary control system (e.g., regulating and shim rods). The safety rods may be suspended above the core by a magnetic clutch coupling and allowed to fall into the core for emergency shutdown. An additional form of safety rod known as a scram rod can be automatically tripped and inserted when dangerous conditions exist; such emergency shutdown is called "scramming" the reactor.

As has been previously stated, control rods are fabricated of cadmium, boron, or hafnium.

c. Reflectors

If a reactor core were not enclosed within a shroud or container, a large number of neutrons would escape and leak out. To minimize neutron leakage, the region which contains the nuclear fuel is surrounded with a good scattering material known as a reflector. The reflector actually scatters back the neutrons into the chain-reacting area. This reflecting back of neutrons reduces leakage from the core and results in a saving of fissionable material because the reflector enables a reactor to become critical when the reactor dimensions are appreciably less than those required for a bare reactor.

f. Shielding

A shield is a body of material that is used to prevent or reduce the passage of particles or radiation. A shield may be designed according to what it is intended to absorb, as a gamma-ray shield, or neutron shield; or according to the kind of protection it is intended to give, as a background, biological, or thermal shield. The shield of a nuclear reactor is a body of material surrounding the reactor to prevent the escape of neutrons and radiation into a protected area.

Frequently this area is the entire space external to the reactor. Shielding may be required for the safety of personnel or to reduce radiation sufficiently to allow use of counting instruments for locating contamination or airborne radioactivity.

The type of shield that is suitable for a particular reactor is dependent upon the purpose of the reactor. For example, an experimental, low power reactor may require little or no shielding whereas a high power reactor would require a shield of considerable thickness. Shielding of a reactor involves (1) slowing down the fast neutrons, (2) capturing the slowed-down neutrons, and (3) absorbing the gamma rays. Two types of shields may be found around a reactor. A thermal shield is sometimes constructed close to the reactor. This shield is usually made of a dense metal with a fairly high melting point, e.g., iron, and is placed between the reactor core and the main shield, referred to as the biological shield. On stationary reactors the biological shield consists of several feet of concrete, used primarily because of its low cost. On mobile reactors the biological shield may be made of lead. In addition to the lead, some of the ship's structure such as beams, girders, plates, and tanks may also serve as shielding materials.

g. Structural Materials

All reactors have structural material which serves as a mechanical framework for the reactor components. Some general characteristics of reactor structural materials are (1) high thermal conductivity; (2) low coefficient of thermal expansion; (3) high corrosion and erosion resistance; (4) relatively low neutron absorption; (5) adequate tensile strength, impact strength, and rupture stress for operating conditions; and (6) ease of fabrication. Some of the metals used in the construction of reactors are aluminum, beryllium, magnesium, molybdenum, chromium, copper, nickel, titanium, stainless steel, and zirconium. The latter metal was actually created as a direct result of our nuclear reactor construction program.

164. REACTOR IDENTIFICATION

Nuclear reactors are machines for putting nuclear energy to work under controlled conditions. Reactors vary according to the purpose for which they are intended. Some operate at temperatures below the boiling point of water, others generate heat which must be carried off or put to work by the use of water, molten metals, etc., as coolants. Some reactors--so called fast reactors--use high-energy neutrons to cause fission; other reactors are utilized to breed fissionable material. At the present time, there are five basic types of reactors included in the American reactor development program. This program represents the joint efforts of the U. S. Navy, the U. S. Atomic Energy Commission, and our vast industrial public. The five basic types of reactors in use and undergoing further experimentation and development are the Pressurized Water Reactor (PWR), the Sodium Cooled Reactor, the Experimental Boiling Water Reactor (EBWR), the Homogenous Reactor (HR), and the Breeder Reactor (BR). A sixth type of reactor which is in the process of study is the British Calder Hall Reactor, a gas-cooled design. The discussion in this chapter will confine itself to a detailed consideration of the stationary pressurized water reactor at Shippingport, Pa., because this installation is basically similar to a naval reactor except for size. The remaining four reactors will be covered briefly by presenting only pertinent information and necessary illustrative material.

165. PRESSURIZED WATER REACTOR (PWR)

The stationary PWR reactor is a thermal, heterogenous type and is fueled with slightly enriched uranium. The basic schematic diagram of the reactor and the steam plant is shown in figure 71. The nuclear reactor is the heat source and produces a minimum full power rating of 790 x 10^6 Btu/hr. This heat is produced in a nuclear core, which is a cylinder consisting of assemblies of enriched uranium in clad[8] plates and natural uranium in tubes. These assemblies are supported in a bottom plate and top grid, which, in turn, are supported from a ledge of the reactor pressure vessel. This reactor vessel is a cylinder with a hemispherical bottom and a removable hemispherical top closure.

The reactor plant consists of a single reactor heat source with four main coolant loops. Coolant[9] enters through four nozzles at the bottom of the reactor and leaves through four nozzles at the top. Three of these loops are required for producing the 60,000 kw minimum design power. Each loop consists of a single-stage centrifugal canned motor pump, a heat exchanger section of a steam generator, 16-inch gate type isolation valves, and the necessary 18-inch outside diameter interconnecting piping.

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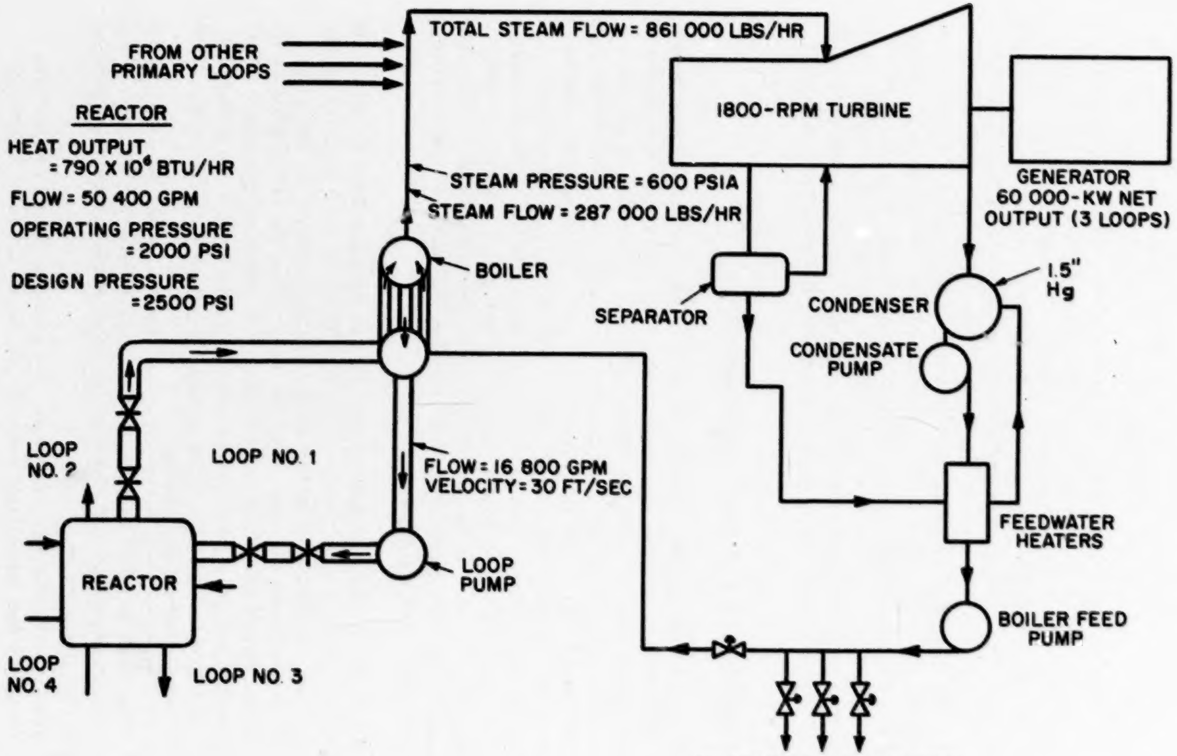
[8] Fuel must be clad to prevent chemical attack by the coolant and to prevent contamination of the coolant with radioactive fuel particles and fission products.

[9] The coolant circuit is called the primary loop, the working fluid is called the secondary loop. Where three or more loops are necessary, intermediate loops are inserted between the primary and secondary loops.


FROM OTHER PRIMARY LOOPS
REACTOR
HEAT OUTPUT = 790 X 10⁶ BTU/HR
FLOW = 50 400 GPM
OPERATING PRESSURE = 2000 PSI
DESIGN PRESSURE = 2500 PSI
TOTAL STEAM FLOW = 861 000 LBS/HR
1800-RPM TURBINE
GENERATOR 60 000-KW NET OUTPUT (3 LOOPS)
STEAM PRESSURE = 600 PSIA
STEAM FLOW = 287 000 LBS/HR
BOILER
SEPARATOR
CONDENSER
1.5" Hg
CONDENSATE PUMP
LOOP NO. 2
LOOP NO. 1
FLOW = 16 800 GPM
VELOCITY = 30 FT/SEC
FEEDWATER HEATERS
REACTOR
LOOP PUMP
BOILER FEED PUMP
LOOP NO. 4
LOOP NO. 3
TO OTHER PRIMARY LOOPS

Courtesy of Westinghouse Electric Corp.

Figure 71. Schematic of a PWR plant

The use of four loops gives the plant considerable operating flexibility because any one or even two loops can be shut down and even repaired without shutting down the remaining loops. The shielding between loops makes this possible from a radiation standpoint.

High-purity light water serves as both coolant and moderator in this plant. This water is under a pressure of 2000 pounds per square inch (psi).[10] The flow through the nuclear core is 45,000 gallons per minute (gpm) for three loops. At full power the inlet water temperature to the reactor is 508° F and the outlet temperature is 524° F. The water velocity in the 18-inch pipes is approximately 30 ft/sec, with a velocity of between 10 and 20 ft/sec in various parts of the nuclear core. The total pressure drop around the main coolant loop is 105 psi, and this drop is divided roughly equally between core, steam generators, and piping.

The coolant enters the bottom of the reactor vessel where 90 percent of the water flows upward between the fuel plates and rods, with the remainder bypassing the core in order to adequately cool the walls of the reactor vessel and the thermal shield. After having absrobed heat as it goes through the core, the water leaves the top of the reactor vessel through the outlet nozzles. The water then passes through two 16-inch isolation valves in series and goes through the heat exchanger section of the steam generator. The water then flows through the canned motor pump and back through the inlet isolation valves to the bottom of the reactor, completing the cycle.

Isolation valves are located immediately adjacent to the reactor inlet and outlet nozzles of each of the four loops. These valves permit isolation of any loop of the reactor plant, to provide maximum protection to the reactor and so that maintenance can be performed while the remainder of the loops are in operation. Shielding is provided to permit this.

The main coolant flows through the inside of many hundreds of small stainless steel tubes in the heat-exchanger section of the steam generators. These heat-exchanger tubes are surrounded by the water of the secondary system, which is thus heated by the primary coolant in the tubes. Wet steam[11] is formed. This wet steam moves upward through risers and enters the steam-separator portion of the steam generator. Here the moisture is removed and returned to the heat-exchanger section through the downcomers. At full power, the dry saturated steam leaves the top of the steam separator at 600 pounds per square inch absolute (psia)[12] and goes to the steam turbine.

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[10] psi is the gauge pressure.

[11] "Wet steam" is the term used to describe saturated steam that contains an unusually large amount of entrained moisture.

a. Major Components

To restrict the spread of radioactivity in the event of a dual casualty (i.e., rupture of the primary coolant system and subsequent melting of the nuclear core with attendant release of fission products) the nuclear part of the plant is completely inside a steel container. This container is sized to contain the pressure created by a rupture of the primary coolant system of the most adverse size, including the effect of the stored energy in the water and the metal as well as any conceivable energy release due to a zirconium-water reaction.

The plant container is divided into four units connected by large tubular ducts. The reactor vessel is located in the spherical section, and two of the main coolant loops are in each of the adjacent cylindrical sections. The fourth cylindrical section is connected into the other three and contains the auxiliary systems.

(1) Reactor Vessel.--The reactor vessel shown in figure 72 has an over-all height of 33 feet, with a cylindrical section which has an internal diameter of about 9 feet and a nominal wall thickness of 8 1/2 inches. The total estimated dry weight of the reactor vessel is 250 tons.

The vessel is formed of carbon-steel plates and forgings with a 0.25 inch stainless steel cladding. The flange for the closure is 9 feet in internal diameter and 23 inches square in cross section. The hemispherical closure head is forged, and has a thickness of about 10 inches, with adequate reinforcement for the 24 control-rod penetrations and the 9 fuel-port tubes.

The vessel is supported by the neutron shield tank at a point just below the vessel flange. This permits the vessel to grow due to thermal expansion with a minimum increase in main-loop piping stresses. The entire vessel is thermally insulated with about 4 inches of glass-wool insulation.

The core assemblies are supported in a stainless steel cage consisting of a barrel, a bottom plate, and a support grid. The cage is nearly 8 feet in outside diameter and slightly over 13 feet high.

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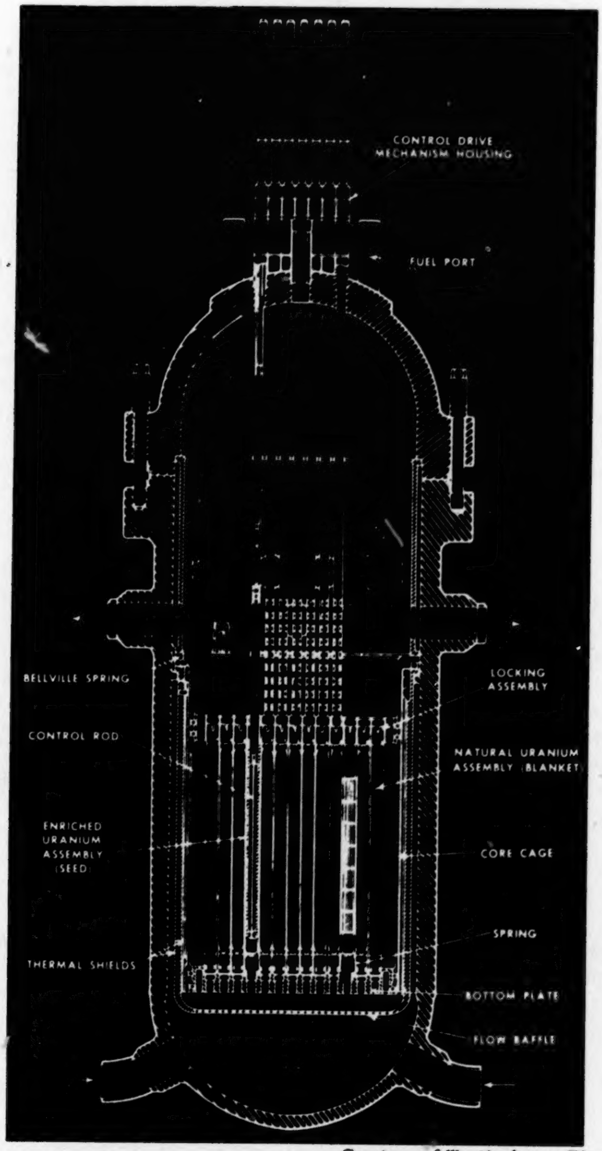
[12] psia is equal to the gauge pressure plus atmospheric pressure.


CONTROL DRIVE MECHANISM HOUSING
FUEL PORT
BELLVILLE SPRING
LOCKING ASSEMBLY
CONTROL ROD
NATURAL URANIUM ASSEMBLY (BLANKET)
ENRICHED URANIUM ASSEMBLY (SEED)
CORE CAGE
SPRING
THERMAL SHIELDS
BOTTOM PLATE
FLOW BAFFLE

Courtesy of Westinghouse Electric Corp.

Figure 72. Longitudinal Section of PWR Reactor

(2) Main Coolant Pumps.--A pump in each of the loops circulates coolant. The pump utilizes a single-winding motor of 1200-kw capacity, which can be connected for two speeds. Power supply is 2300 volts, 60 cycles per second, 3 phase, for both speeds. The motor, weighing about 20,000 pounds, is mounted in the case stainless steel volute.

(3) Main Stop Valves.--Two hydraulically operated main stop valves are required in each loop, or eight for the plant. One of these valves is a parallel-disk gate valve, hermetically sealed and provided with an integral cylinder and piston. Latches hold it in the closed position. The nominal size of the valve opening is 16 inches, with ports tapered to an 18-inch pipe size.

The valve is designed for normal operation at differential pressures of 600 to 1000 psi across the piston, but can withstand stresses resulting from emergency application of a 3000 psi differential pressure. This valve will shut off against a maximum differential gate pressure of 600 psi, although normal shutoff pressure is a maximum of 210 psia. Position indicators show when the valve is fully open or fully closed. Eight manual valves serve as backups for the hydraulically operated stop valves.

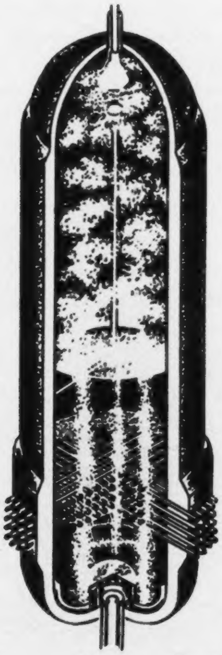
(4) Steam Generators.--The steam generators are each rated at 263 x 10^6 Btu/hr and provide 600 psia full-power steam pressure; this pressure rises to 885 psia at no load. The secondary-side design pressure is 975 psia. The primary-side operating pressure is 2000 psi, with a design pressure of 2500 psi. Six and a half million pounds, or approximately one million gallons per hour of primary cooling water pass through the tubes, entering at a temperature of 542° F and leaving at 508° F. Two of these units are entirely of stainless steel and are of a straight tube, fixed-tube sheet design. They are 36 feet long and 43 inches in diameter.

The other two units are of a return band of U-tube type. The over-all length is 28 feet, and the diameter is 39 inches.

Steam generators of the two different types are used so that experience can be gained in the design, manufacture, and operation of both types to give more knowledge on which to base the design of future plants.

(5) Pressurizing Tank.--A cutaway perspective of the pressurizing tank is shown in figure 73. The tank is 18 feet high and 5 feet in inside diameter with a total volume of 300 cubic feet, of which about 150 cubic feet is the steam dome: Normal surges will be

as great as plus or minus 10 cubic feet under design plant-load fluctuations. Under these design conditions primary system pressures will be held within limits of 1850 to 2185 psia. A 6-inch surge line in the bottom head connects this tank with the primary coolant system.



Courtesy of Westinghouse Electric Corp.

Figure 73. Cutaway
View of
Pressurizing Tank

The heater section contains 200 heater wells, into which are inserted 500 kilowatts of replaceable electric heaters. These are arranged electrically into three groups for operational convenience and are controlled to maintain a saturation temperature of 636° F (corresponding to a pressure of 2000 psia), and to form a steam bubble in the top of the tank. A spray nozzle at the top sprays colder (500° F) water into the steam during positive surges to help limit maximum pressures. Located in the center of the tank is a standpipe

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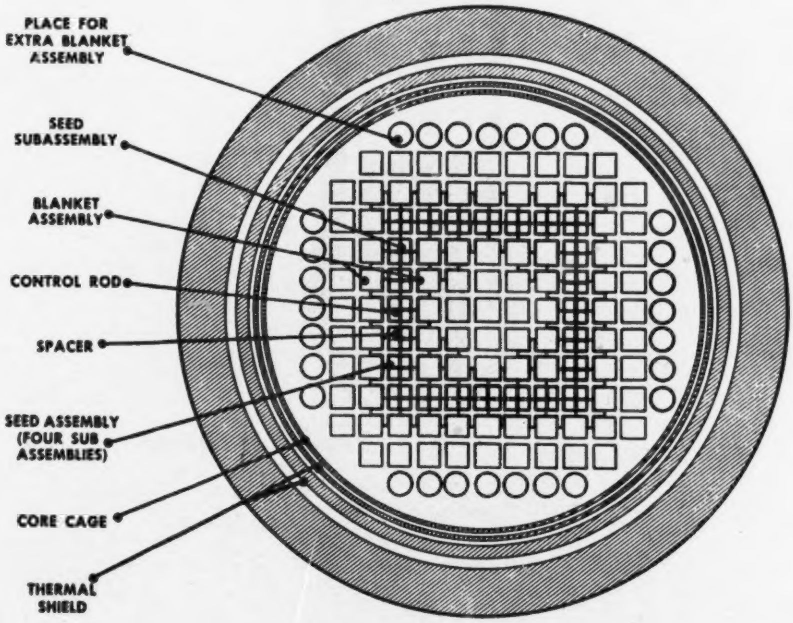
for use as a reference leg for water-level measurement. A low-level alarm warns the operator to add water to the system before the level drops to a point where negative surges could uncover heater wells.

(6) Core Design. --The active portion of the nuclear core is in the form of a cylinder 6 feet in mean diameter and 6 feet high. To minimize the amount of enriched U^{235} used, the core consists of some highly enriched seed and some natural blanket assemblies. The highly enriched, or seed assemblies are located in a square annular region about 6 inches thick. The area inside and outside of the annulus is filled with natural uranium oxide subassemblies. A cross section of the core is shown in figure 74.


PLACE FOR EXTRA BLANKET ASSEMBLY
SEED SUBASSEMBLY
BLANKET ASSEMBLY
CONTROL ROD
SPACER
SEED ASSEMBLY (FOUR SUB ASSEMBLIES)
CORE CAGE
THERMAL SHIELD

Courtesy of Westinghouse Electric Corp.

Figure 74. Cross-Sectional View of Reactor and Core

Each seed subassembly consists of several plates welded together to form a box. Four of these box-type units are welded together, with separation maintained by spacers, to form a central cruciform-shaped area. In each of these areas is located a cruciform-shaped hafnium control rod.

The uranium oxide, or blanket assemblies use a rod as the basic element. These rods are Zircaloy-2 tubing. The tubes are filled with UO_2 pellets and have Zircaloy-2 end plugs welded to each end to form fuel rods. These rods are assembled into bundles of 100 rods each; the assembly is made by mechanically fastening together a stack of seven bundles, each 10 inches long, for a total of about 6 feet.

b. Primary Auxiliary Systems

A number of auxiliary systems are connected into the primary coolant circuit to ensure proper operation of the plant. Some of these, such as the pressurizing system and the purification system, are in use continuously, while others are required for intermittent operation. In addition, there are the usual power-plant auxiliary systems such as cooling water, compressed air, and electrical.

(1) Coolant Charging System.--The coolant charging system is used for filling the primary plant prior to operation and for maintaining the proper fluid level in the pressurizer. One 100-gpm low-head pump is used for filling and two 25-gpm high-pressure pumps are required for the intermittent makeup function. The charging system also contains facilities for charging fresh resin into the purification demineralizer and back-flushing the primary loops. No purification equipment is provided in this system, as the water from the boiler makeup-water equipment meets primary water specifications.

(2) Pressurizing System.--Changes in the core average temperature due to power demands and changes in reactivity, and subsequent correction by control-rod movement make the system coolant volume a variable. These volume changes would cause wide variations in coolant-system pressure if the plant were operated as a solid system. The function of the pressurizer is to regulate the system pressure within a lower limit set by the reactor hot-spot temperature, and an upper limit determined by the safety and relief-valve settings. The relief pressurizing system maintains a 2000 psi saturation steam head in a separately heated pressurizing vessel. This vessel has a volume of approximately 300 cubic feet, and contains about 100 cubic feet of water. The size is a function of the total volume of coolant and the transport time of water in loops, as well as the rate of change of power. The heat to the pressurizing vessel is supplied by 500 kw of electric immersion heaters, which are sufficient to raise the temperature of the water in the pressurized tank consistent with 200° F/hr heating rate for the entire plant.

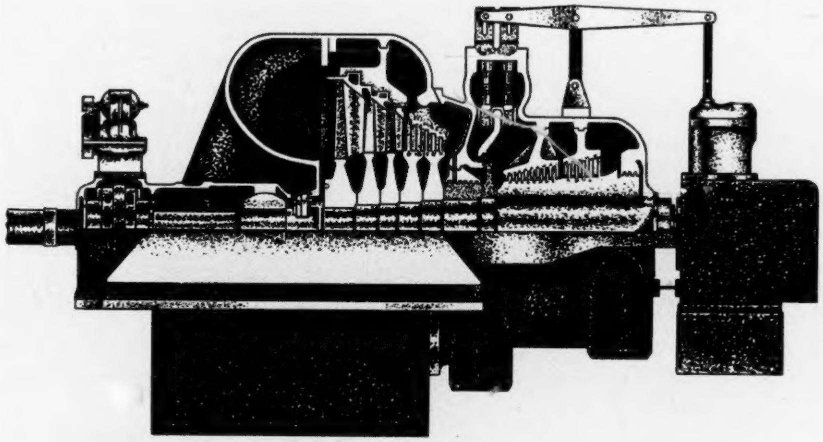
(3) Purification System. --A fraction of the coolant that passes through the nuclear core must be purified to limit the activity build-up of the long-lived impurities in the water. This is done by passing a certain quantity of the coolant through a bypass demineralizer, which removes soluble and insoluble matter. The reactor coolant-purification system consists of two parallel loops, each of which provides purification for two of the four reactor coolant loops.

(4) Waste-Disposal System. --The activity in the ion-exchange resin from the purification system and in the decontamination fluids and primary system effluent will be too high to permit dumping in the river. The volumes involved make packaging and subsequent disposal at sea infeasible. The waste disposal system now being developed will consist of two-stage evaporation, to reduce bulk, and subsequent underground storage of high-activity evaporator residue at the site.

Spent resin from the demineralizers will be transferred by flushing, in the form of a slurry, directly to underground storage. Provision for collection and storage of radioactive gases is being made. Dilution and discharge through a vent stack will be used when meteorological conditions permit. The evaporator feed will be from 9000 to 21,000 cubic feet per month depending primarily on decontamination procedure. Evaporator vapor will be condensed and then diluted with condenser cooling water before release to the river. The permissible activity released to the river is being taken at ten percent of the standard tolerance. A study is underway to determine the most economical method for disposing of combustible radioactive waste. The methods being considered are an incinerator at the site, or baling and shipping for disposal at sea. High and low activity laboratory wastes will be separated at the source and processed through the evaporator or diluted and dumped as dictated by the activity.

c. Turbogenerator

The turbogenerator is rated at 100 megawatts maximum capability and is a single cylinder, 1800-rpm unit with direct-connected exciter. The turbine has three points of steam extraction for feedwater heating. As shown in figure 75, steam is admitted at some distance from the thrust-bearing end of the rotor, flows toward the thrust-bearing, and passes to an external moisture separator. It then passes back into the turbine at a point near the original point of entrance, from which it flows in a direction away from the thrust-bearing to exhaust at the coupling end.



Courtesy of Westinghouse Electric Corp.

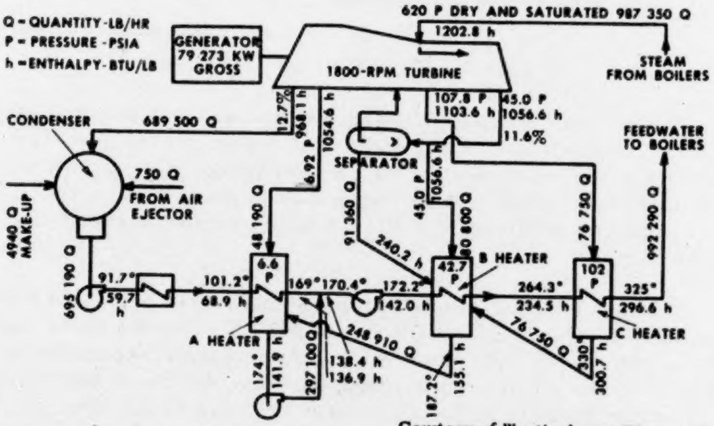
Figure 75. Turbine Cross Section

The cylinder barrel, between blade rows, is lined with stainless steel, and all blades are Stellite-faced on the leading edges wherever moisture content of the steam exceeds six percent and blade-tip speed is 900 feet per second or higher. These precautions are expected to minimize the effects of wet steam on life of the turbine parts.

The full-load-throttle steam pressure is 545 psig, and the corresponding feed water temperature is 342° F. The moisture content at the second extraction point, where the moisture separator is located, will be about 11.6 percent, and this will be reduced to approximately one percent for the steam returned to the turbine. Under these same full-load conditions the exhaust moisture will be on the order of 13.2 percent. This information, together with performance heat rates, is shown in table II for two loads, and the turbine steam-cycle diagram is shown in figure 76.

As load is reduced slowly under normal conditions of extraction and exhaust back-pressure, the steam flow, the heat transmitted in the boiler heat exchangers, and the temperature difference from coolant to steam will all become less. Except during transients, the mean temperature of the reactor primary-coolant water will remain constant, and hence the boiling-water temperature and pressure will rise. This rise is approximately linear and reaches a maximum of 870 psig at zero steam flow.

TABLE II Performance Heat Rates	Gross Generator Load--Megawatts	
	79.3	100
Turbine heat rate, gross (Btu/kwh)	11,272	11,385
Throttle pressure (psia)	620	560
Throttle flow (16/hr)	987,350	1,286,900
Boiler feed temperature (degrees F.)	325	342
Condenser vacuum (in Hg)	1.5	1.5


Q - QUANTITY-LB/HR
P - PRESSURE-PSIA
h - ENTHALPY-BTU/LB
GENERATOR 79 273 KW GROSS
1800-RPM TURBINE
620 P DRY AND SATURATED 987 350 Q
1202.8 h
STEAM FROM BOILERS
12.7%
6.92 P 968.1 h
1054.6 h
107.8 P 1103.6 h
45.0 P 1056.6 h
11.6%
CONDENSER
689 500 Q
750 Q
FROM AIR EJECTOR
4940 Q MAKE-UP
SEPARATOR
FEEDWATER TO BOILERS
48 190 Q
91 360 Q
45.0 P 1056.6 h
60 800 Q
76 750 Q
992 290 Q
240.2 h
B HEATER
695 190 Q
91.7°
59.7 h
101.2°
68.9 h
6.6 P
169°
170.4°
172.2°
142.0 h
42.7 P
264.3°
234.5 h
102 P
325°
296.6 h
A HEATER
C HEATER
248 910 Q
76 750 Q
174°
141.9 h
297 100 Q
138.4 h
136.9 h
187.2°
155.1 h
330°
300.7 h

Courtesy of Westinghouse Electric Corp.

Figure 76. Heat Balance Diagram

The thermal efficiency of a simple condensing cycle utilizing steam at 545 psig saturated and exhausting at 1 1/2 inches of mercury absolute is 26.5 percent. This is raised to 29.5 percent by converting to the regenerative cycle of the type described. Since thermal losses of the reactor and its appurtenances are low, the turbine-cycle efficiency after allowance for auxiliary requirements may be considered for practical purposes to be the thermal efficiency of the over-all plant.

The station-service power requirements are estimated to be 6000 kw for the nuclear portion of the station, and 3500 kw for the turbogenerator portion. The principal items in the former are the four primary-coolant pump drives totaling 4800 kw. In the turbogenerator portion, the largest auxiliaries are the main-condenser circulating-water pumps, of which there are two at 900 hp each. These pumps operate at a substantially higher head than is usual for such pumps, due to characteristics of the terrain and the plant elevation required by occasional floods of the Ohio River at this point.

The turbogenerator will be an outdoor type located on a deck, below which the condenser and auxiliary equipment will be housed. A semigantry crane will operate above the deck for handling turbogenerator equipment for maintenance purposes. The main and station-service transformers will be located at ground level along the river side of the turbine structure. To protect the turbogenerator and personnel in this area from the effects of a possible transformer-oil fire, a heat-resisting barrier will be placed along the turbine side of the transformer area.

The station-service buses supplying power for auxiliaries in both the nuclear and turbogenerator portions of the station will be arranged in four sections, two served from separate secondaries of a transformer connected to the main-generator leads, and two served from separate secondaries of a transformer connected to the 138-kv transmission bus. The four primary-coolant pumps will then be served, one from each of these four sections, and supply to other auxiliaries will be divided among them in such a way as to provide maximum security of service. A diesel generator of approximately 750-kw capacity will be provided to operate certain essential plant components in the remote possibility of total loss of other power sources. These components and their functions are: coolant pumps for reactor decay heat, emergency lighting, storage-battery charging, and turbogenerator turning-gear operation.

In addition to the system described above, there are many close connections between the turbogenerator and reactor portions of the power station. In general, the supplies of water for charging, cooling, and other purposes originate in the turbogenerator portion as well as communications arrangements involving the telephone and loud-speaker systems, sources for electric power and main and emergency lighting of the plant.

A single control room is provided for centering control of the reactor and its appurtenances, the turbogenerator station service, and the outgoing power circuits. The principal electric circuits and piping arrangements for steam and water are shown pictorially on the control boards, with equipment, processes, switches, and valves shown, and suitable indicating lights placed thereon. This is a safety precaution to aid in minimizing operating errors, and it also presents at a glance the operating setup of the station for guidance of the operators.

166. SODIUM COOLED REACTOR

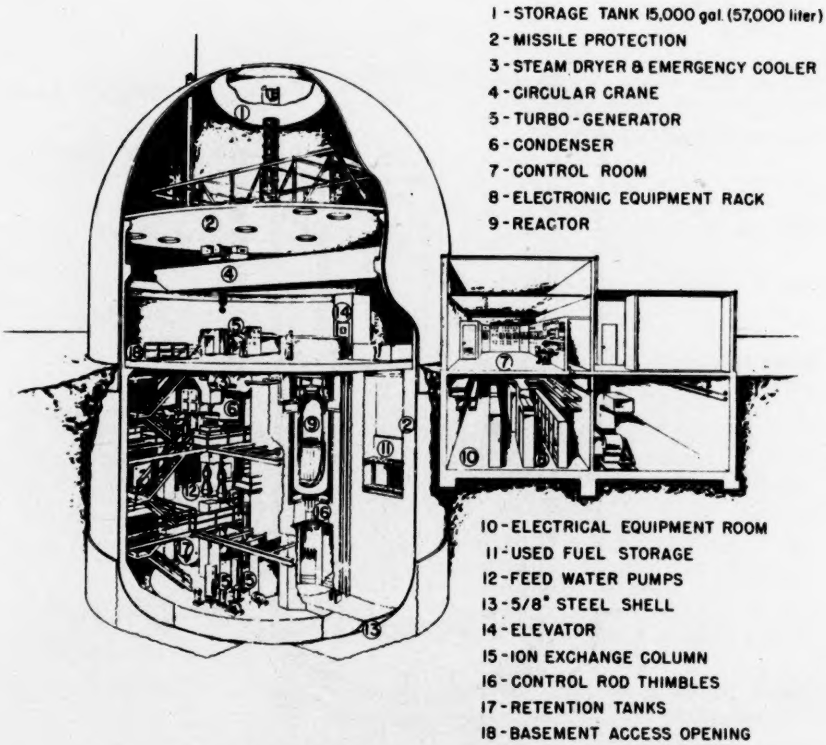
The Navy's second nuclear submarine, USS Seawolf (SSN 575), has a homogeneous type, intermediate reactor which uses liquid sodium as the primary coolant. However, due to the corrosive nature of sodium, the steam generators and superheaters developed leaks. As a result, the superheaters are being bypassed. This limits the operation of Seawolf to 80 percent of designed hp rating and 90 percent of designed maximum speed. Depsite these limitations, the Seawolf is still capable of better performance than any U.S.N. conventional-powered submersible.

167. EXPERIMENTAL BOILING WATER REACTOR (EBWR)

This small atomic power plant (fig. 77) is designed to allow steam to be generated directly in the reactor core (fig. 78) and is classified as a heterogeneous type reactor. The water for the steam cycle also serves as the moderator. The major advantages are elimination of highly pressurized cooling water, and of attendent pumps and heat exchangers. This design also allows production of turbine steam at higher temperature and pressure (fig. 79). The major problems are carryover of radioactivity to the turbine, integrated control of the reactor and power plant, and development of reliable fuel elements.

168. HOMOGENEOUS REACTOR EXPERIMENT (HRE)

The HRE-1 employed as fuel a solution in water of highly enriched uranyl sulfate (UO_2SO_4). It was constructed in 1951 and dismantled early in 1954 after two years of successful experimental operation at the Oak Ridge National Laboratory. It demonstrated (1) a remarkable degree of inherent nuclear stability as a result of the very large negative temperature coefficient of reactivity; (2) the elimination of the need for mechanical control rods as a consequence of this inherent stability; (3) flexibility and simplicity of fuel handling; (4) stability of the fuel; (5) the ability to attain and maintain leak tightness in a small high pressure reactor system; (6) the safe handling of the hydrogen and oxygen produced by radiation decomposition of the water; and (7) direct dependence of reactor power upon turbine demand.



1 - STORAGE TANK 15,000 gal (57,000 liter)
2 - MISSILE PROTECTION
3 - STEAM DRYER & EMERGENCY COOLER
4 - CIRCULAR CRANE
5 - TURBO - GENERATOR
6 - CONDENSER
7 - CONTROL ROOM
8 - ELECTRONIC EQUIPMENT RACK
9 - REACTOR
10 - ELECTRICAL EQUIPMENT ROOM
11 - USED FUEL STORAGE
12 - FEED WATER PUMPS
13 - 5/8" STEEL SHELL
14 - ELEVATOR
15 - ION EXCHANGE COLUMN
16 - CONTROL ROD THIMBLES
17 - RETENTION TANKS
18 - BASEMENT ACCESS OPENING

Figure 77. Plan Perspective of EBWR

The HRE-2, also at the Oak Ridge National Laboratory, represents an advance over the HRE-1 in power, physical size, and quality of construction. It employs as fuel a solution in heavy water, rather than ordinary water, of highly enriched uranyl sulfate in a spherical core (fig. 80). Figure 81 shows the interior of the HRE-2 building. The spherical core and pressure vessel assembly can be seen in the background prior to installation beneath the floor in the background.

The objectives of the HRE-2 are (1) to demonstrate that a homogeneous reactor of moderate size can be operated with the continuity required of a power plant; (2) to establish the reliability of engineering materials and components of a size which can be adopted to full scale power plants; (3) to evaluate equipment modifications which will lead to simplifications and economies; (4) to test simplified maintenance procedures and, in particular, maintenance under

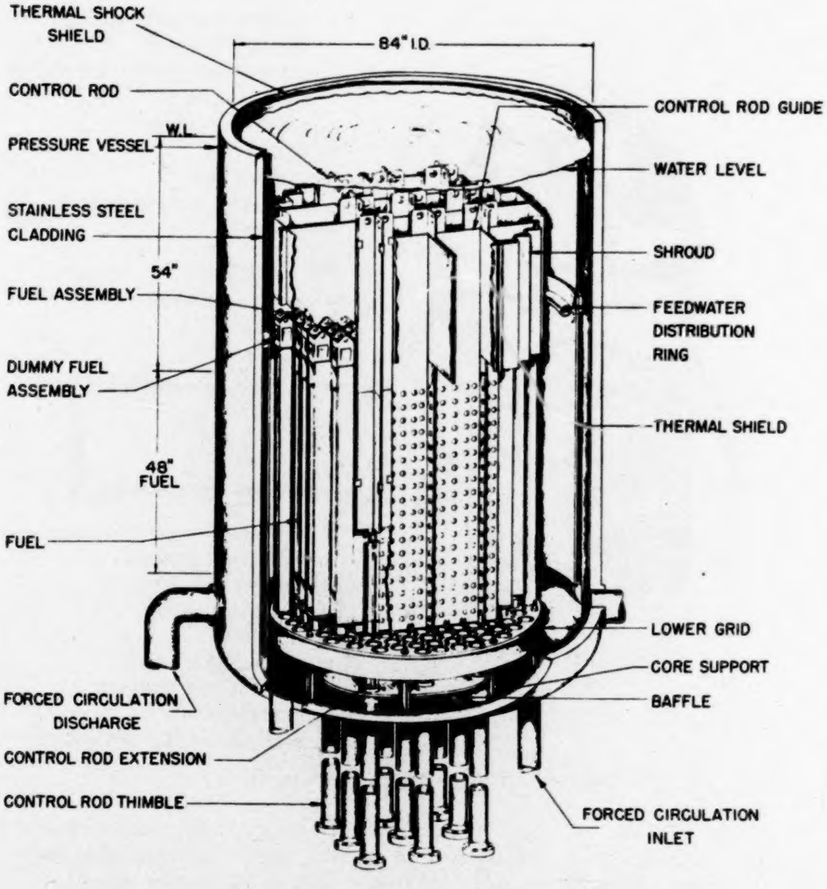

THERMAL SHOCK SHIELD
84" I.D.
CONTROL ROD
CONTROL ROD GUIDE
W.L.
PRESSURE VESSEL
WATER LEVEL
STAINLESS STEEL CLADDING
SHROUD
54"
FUEL ASSEMBLY
FEEDWATER DISTRIBUTION RING
DUMMY FUEL ASSEMBLY
THERMAL SHIELD
48" FUEL
FUEL
LOWER GRID
CORE SUPPORT
FORCED CIRCULATION DISCHARGE
BAFFLE
CONTROL ROD EXTENSION
CONTROL ROD THIMBLE
FORCED CIRCULATION INLET

Figure 78. Perspective of EBWR Core

water; and (5) to develop and test methods for the continuous removal of fission and corrosion contaminants.

169. EXPERIMENTAL BREEDER REACTOR (EBR)

Experience with this heterogeneous reactor at the National Reactor Testing Station in Idaho has demonstrated the feasibility of breeding with fast neutrons. In a trial run on December 21 and 22, 1951, it generated the first useful electric power known to have been produced from atomic fuel.

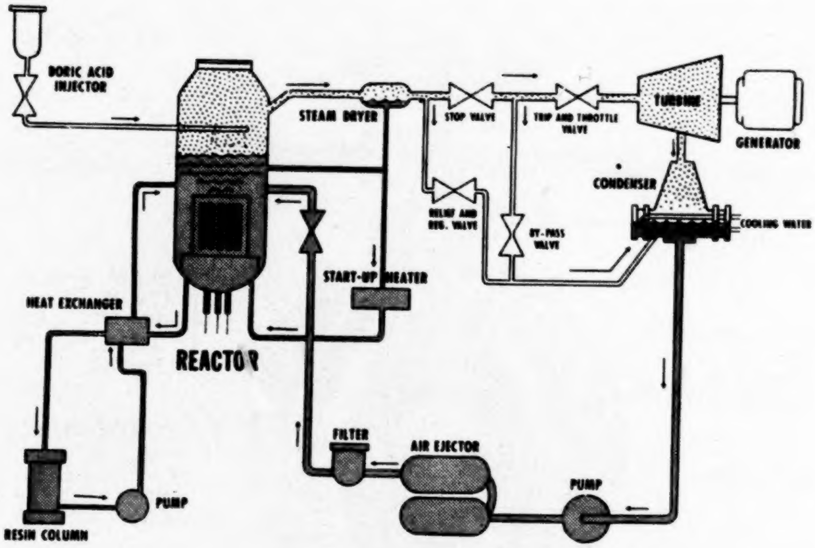

BORIC ACID INJECTOR
STEAM DRYER
STOP VALVE
TRIP AND THROTTLE VALVE
TURBINE
GENERATOR
CONDENSER
COOLING WATER
RELIEF AND REG. VALVE
BY-PASS VALVE
START-UP HEATER
HEAT EXCHANGER
REACTOR
FILTER
AIR EJECTOR
PUMP
PUMP
RESIN COLUMN

Figure 79. EBWR Flow Diagram

In November 1955, in the course of an experiment to determine behavior during sudden power increases, enough heat was produced to cause melting of fuel elements and other damage to the core. It is planned to get the reactor back into operation during the summer or fall of 1957. It will be used for experiments to determine the effects of the bowing of fuel elements on reactor behavior.

Figure 82 shows a general view of breeder reactor. Heavy shielding concrete encloses the graphite reflector, outer and inner natural uranium breeder blanket and highly enriched uranium core. The core itself, a hexagonal prism only 7 1/2 inches high, is at the center of the structure about four feet above floor level. The control room is at the head of the stairs.

Figure 83 shows a horizontal section and perspective view of how the inner and outer blanket and the reflector fit around the core. Both inner blanket rods and outer blanket bricks are clad with stainless steel.

170. PROBLEMS ASSOCIATED WITH NUCLEAR POWER

The problems which faced the developers of nuclear power were twofold. First were those unique to atomic energy--such as the

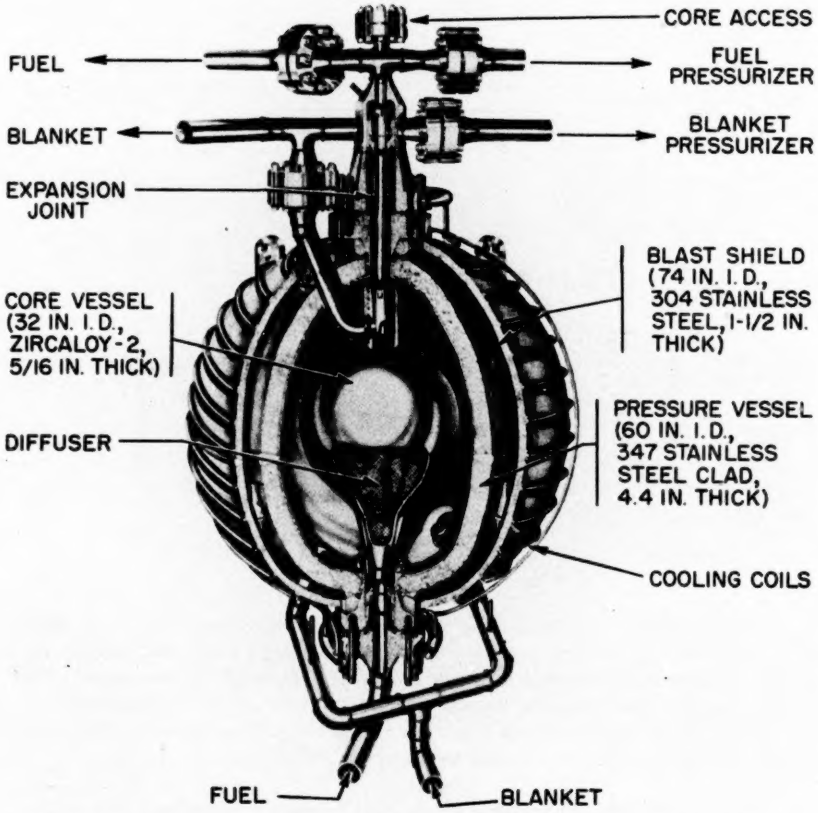

CORE ACCESS
FUEL
FUEL PRESSURIZER
BLANKET
BLANKET PRESSURIZER
EXPANSION JOINT
BLAST SHIELD (74 IN. I. D., 304 STAINLESS STEEL, 1-1/2 IN. THICK)
CORE VESSEL (32 IN. I. D., ZIRCALOY-2, 5/16 IN. THICK)
PRESSURE VESSEL (60 IN. I. D., 347 STAINLESS STEEL CLAD, 4.4 IN. THICK)
DIFFUSER
COOLING COILS
FUEL
BLANKET

Figure 80. Cutaway Perspective of HRE-2 Reactor Assembly

fuel elements and other reactor components that use uranium, zirconium, or beryllium and which must withstand the impact of the nuclear fission process. Second were the problems design engineers have with conventional materials and components--such as carbon steels and stainless steels which are used in valves and heat exchangers; these are just as important as the special materials.

It is common belief that atomic power development was primarily the province of the nuclear physicist. Nothing could be further from the truth. What actually faced the nuclear-power developers was how to determine, by calculation and by experiment, the best way to remove heat from a reactor; and then to design and build all of the components of the reactor system so that they would operate safely and reliably under the most rigorous conditions.

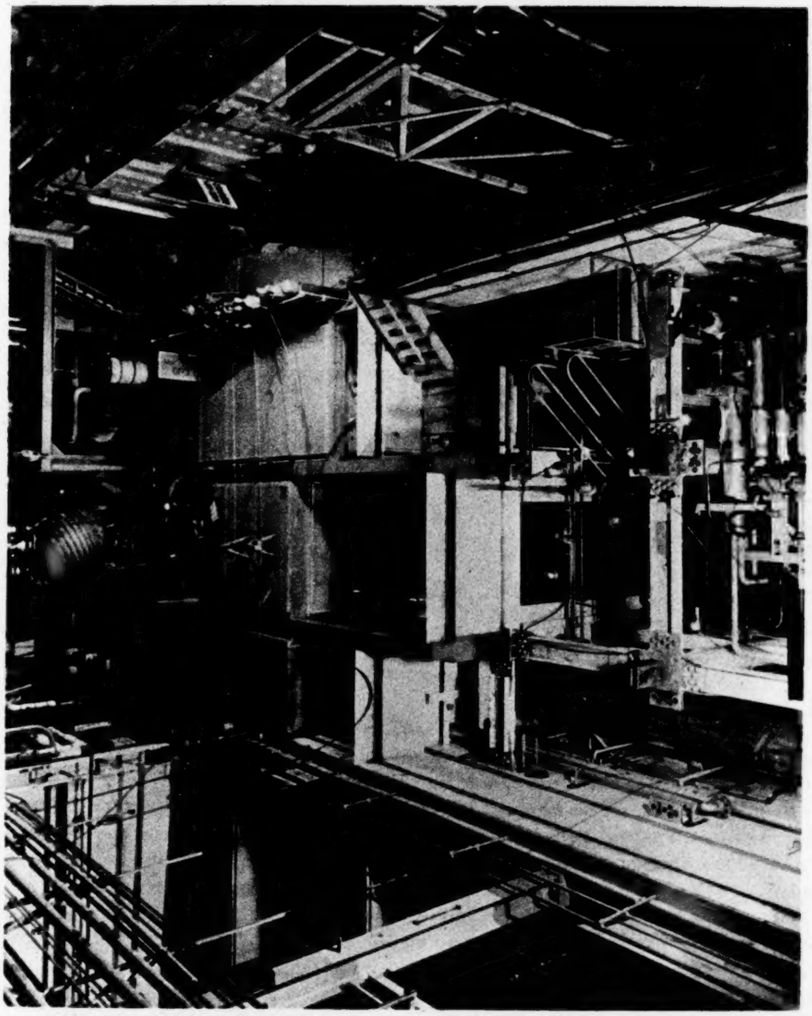


Figure 81. Interior of HRE-2 Building

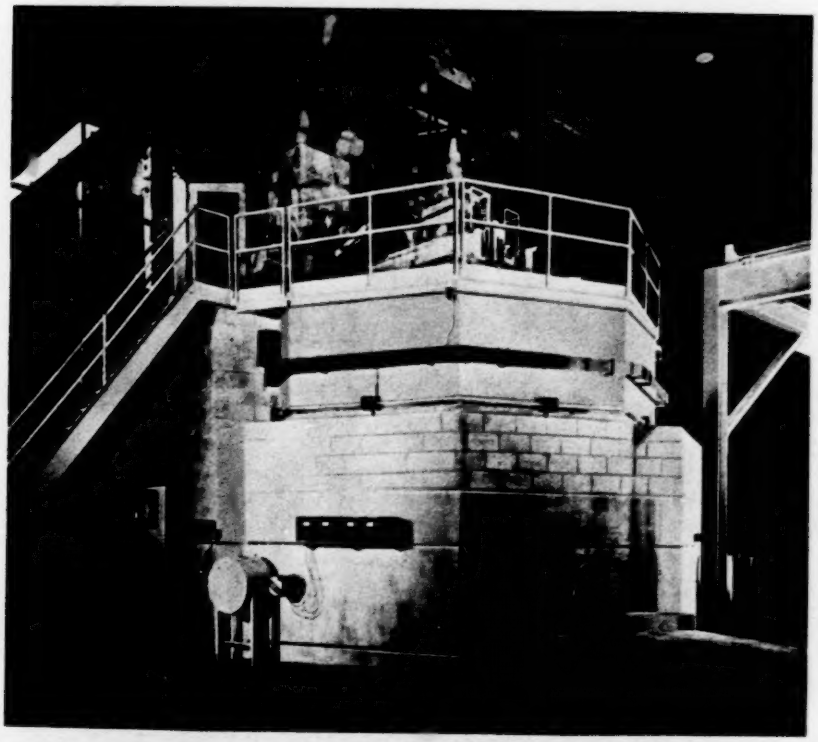


Figure 82. General View of EBR-1

The problems included the familiar ones of using materials at high temperature and pressure. They also included the ability to withstand corrosion to a very high degree. The new problems raised by atomic power were caused by the fact that in nuclear fission heat is generated inside a fuel element and proceeds outward, whereas in a chemical combustion process the heat is applied from the outside and proceeds inward. Chemical combustion reactions are normally limited to a maximum of about 3000° F, but in nuclear fission, temperatures of millions of degrees can be achieved. Moreover, the nuclear-power developers were faced with radioactivity and its tendency to distort and to weaken materials. The fact that many materials capture neutrons and thus tend to stop the chain reaction severely restricted the developers in their choice of materials.

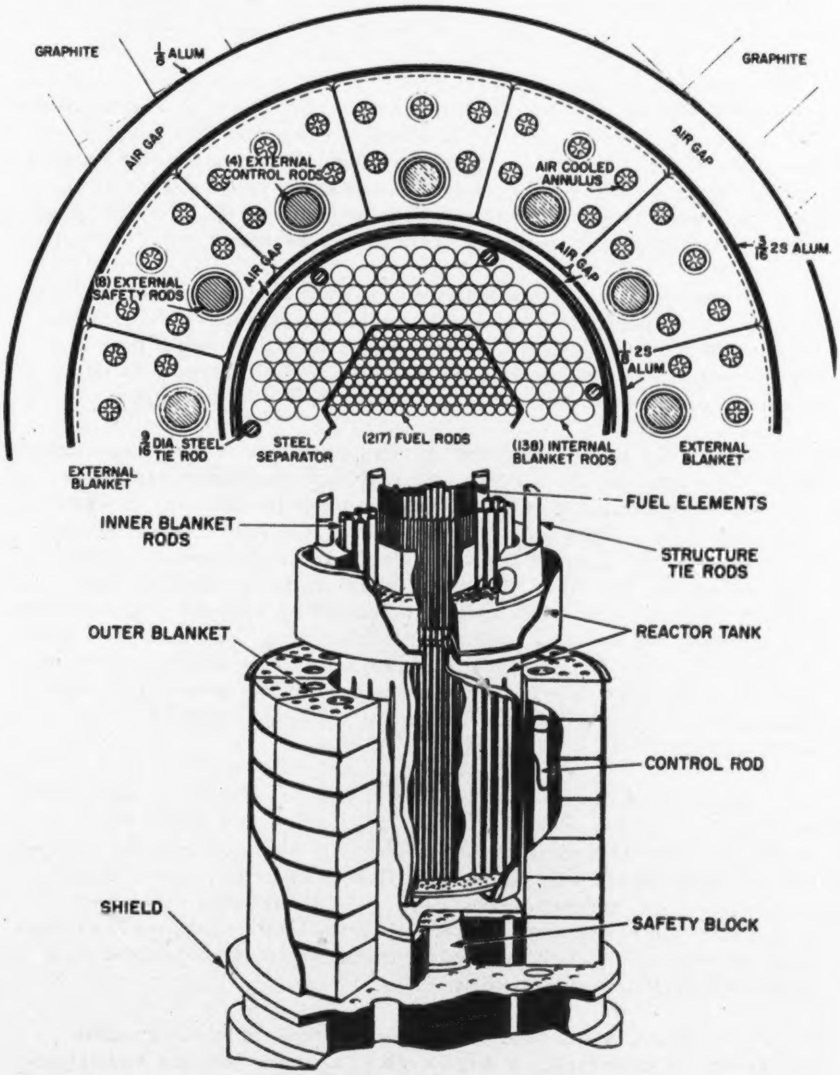

GRAPHITE
$\frac{1}{8}$ ALUM
GRAPHITE
AIR GAP
AIR GAP
(4) EXTERNAL CONTROL RODS
AIR COOLED ANNULUS
$\frac{3}{16}$ 2S ALUM.
AIR GAP
AIR GAP
(8) EXTERNAL SAFETY RODS
$\frac{1}{8}$ 2S ALUM.
$\frac{3}{16}$ DIA. STEEL TIE ROD
STEEL SEPARATOR
(217) FUEL RODS
(138) INTERNAL BLANKET RODS
EXTERNAL BLANKET
EXTERNAL BLANKET
FUEL ELEMENTS
INNER BLANKET RODS
STRUCTURE TIE RODS
OUTER BLANKET
REACTOR TANK
CONTROL ROD
SHIELD
SAFETY BLOCK

Figure 83. EBR-1 Core

First of all, the development of suitable reactor fuel elements was the greatest problem to be faced. As we know, the fuel elements are those parts of the reactor core that contain the fissionable material which produces the heat, and hence must withstand high temperatures and the radiation impact of the fission process. Changes in form and substance in fuel elements are inherent in the operation of a reactor. And yet these changes must not be allowed to destroy the over-all integrity of the fuel element nor interfere with the functioning of a complex reactor with its close tolerances. The service demands on fuel elements are greater than those in any other application. Work on fuel elements is a challenging new field which is receiving wide attention, and in which millions of dollars are being spent. Much creative work still remains to be done.

A most challenging problem in reactor design presented itself from the very beginning--a metals problem. Noncorrosive, radiation and heat resistant metals were required--this was a problem for the metallurgists because the concept of the molecule is not needed, nor in most cases can it be used by the metallurgist.

One of the many problems in reactor design was the development of zirconium. Zirconium was selected because it had a low cross section for the capture of neutrons and in addition, it was supposed to be corrosion resistant. Little was known about zirconium's engineering properties nor was it in production on a commercial scale. The first pound of zirconium to be used for fuel element lattices cost $300 as compared with a current price of about $12 a pound. While the production problem was being solved it was learned that zirconium had corrosion qualities unsuitable for reactor use. An integrated crash program between industry and Government got underway and produced a corrosion resistant form of zirconium--Zircaloy-2.

Another example of the combined efforts of industry and Government was in the development of new aluminum alloys. Fuel elements are clad with aluminum because it is cheaper than zirconium and has as good nuclear characteristics. The problem was that for power reactors, temperatures were so high that they caused excessive corrosion of the available aluminum alloys. Again a crash program developed an aluminum alloy which would withstand the high temperature of power reactors.

In addition to the problems of fuel elements and corrosion resistance of materials, a third area of concern was the application of conventional materials to nuclear reactors. Of the conventional materials, stainless steel was the biggest problem. Stainless steel is used in heat exchanger tube sheets, pressure vessels, valve bodies, etc., and in each of these the problem was and still is fabrication and welding.

Thus we see that metallurgy, the science of metals, has become a field of vital importance in the atomic energy program. Particularly in reactor development, intensive research has been necessary to perfect metals and alloys of metals that can perform adequately under the temperatures, pressures, and radiation to which they are exposed. Success of development at nearly every point depends on improvements in available metals.

SECTION II. NAVAL NUCLEAR POWER PLANTS

In addition to its traditional role of sinking ships, in modern warfare the submarine is used for antisubmarine warfare with torpedoes and mines, and for guided missile attacks against fixed and mobile targets. The advent of nuclear power, long-range sonar, and guided missiles has had such a profound effect on the submarine that it must now be considered virtually as a new weapon. Nuclear power gives to the submarine unlimited submerged endurance, greatly increased submerged speeds, and much greater invulnerability to counter-action. When this is combined with long-range sonar, we have an ideal instrument with which to project our ASW systems in depth into enemy waters--to use offensive ASW measures rather than fighting the battle in the vicinity of our convoys or task forces.

Furthermore, nuclear power greatly facilitates the work of the submarine on a mining mission. The combination of the guided missile and the submarine gives the Navy a weapon of unprecedented stealth and secrecy. This submarine can be used to destroy targets of naval interest and, most important in that first phase of ASW, U-boat pens, before enemy submarines have a chance to get to sea.

In the traditional role of sinking ships, the factors of unlimited submerged endurance and greatly increased speeds put into the hands of the submarine's commanding officer an instrument with which he can attack at will. Having consummated an attack, he has a choice--either he can withdraw and come in again, or he can travel in relative security underneath the convoy, sinking ships at will.

The nuclear Navy at the close of 1957 consisted of three operational atomic-powered submarines with sixteen others authorized and one aircraft carrier and one cruiser on the ways.

The atomic powered Nautilus (SSN-571) (fig. 84A) has an overall length of approximately 320 feet, and is approximately 28 feet through a mid-hull cross section. She has a surface displacement of approximately 3000 tons.

SSN-571 represents the latest in submarine conception and design. She is designed to cruise longer, farther, and faster than conventional submersibles. Nautilus has the most powerful nuclear propulsion plant afloat, and can make more than 20 knots submerged.

Conventional submarines operate on batteries while submerged, and even at slow speeds can travel less than 100 miles completely submerged. However, while completely submerged they can snorkel at periscope depth as long as diesel fuel is available. But the Nautilus can girdle the globe without resurfacing, since her atomic powered engine does not require air.

171. ATOMIC SUBMARINE POWER PLANT

The amount of energy that may be released in a reactor, and hence the amount of power that may be produced thereby, does not depend upon the size of the reactor. Any amount of power, from a few watts up to hundreds of thousands of kilowatts of heat may be produced from any size reactor provided this energy can be removed from the reactor.

The application of the heat released in the reactor to the production of useful power, in general, is achieved through a conventional thermodynamic cycle.

The thermodynamic cycle chosen for the Nautilus power plant was one that permits operation at just about the minimum temperatures that allow the generation of useful power. The thermodynamic cycle selected for the submarine thermal reactor uses light water under high pressure to prevent boiling, thus transferring heat from the reactor into a steam generator. This generator is basically a shell-and-tube-type feed water heater. Ordinary boiler water at relatively low pressures on the other side of the tubes (from the primary coolant) boils and forms steam. This steam is used to drive steam turbines for propulsive power and to generate electricity to meet auxiliary electrical requirements.

a. General Plant Layout

The equipment mounted in the hull of a nuclear-powered submarine is so functionally interrelated that it must be considered as a single power plant. However, the equipment requires hull space of such size that it was necessary to divide the space into two physically separated compartments to provide adequate watertight integrity in the event of battle damage to the hull (fig. 84A) and for shielding purposes.

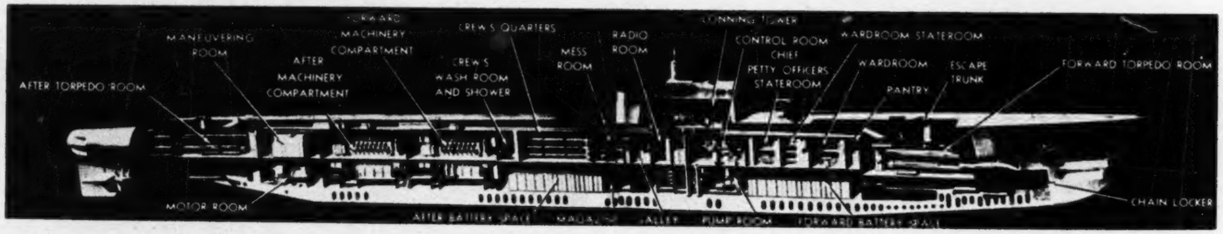

AFTER TORPEDO ROOM
MANEUVERING ROOM
AFTER MACHINERY COMPARTMENT
FORWARD MACHINERY COMPARTMENT
CREW'S QUARTERS
CREW'S WASH ROOM AND SHOWER
MESS ROOM
RADIO ROOM
CONNING TOWER
CONTROL ROOM
CHIEF PETTY OFFICERS STATEROOM
WARDROOM STATEROOM
WARDROOM
PANTRY
ESCAPE TRUNK
FORWARD TORPEDO ROOM
CHAIN LOCKER
MOTOR ROOM
AFTER BATTERY SPACE
MAGAZINE
GALLEY
PUMP ROOM
FORWARD BATTERY SPACE

Figure 84A. Compartmentation and Machinery Arrangement on the U. S. S. Nautilus (SSN-571)

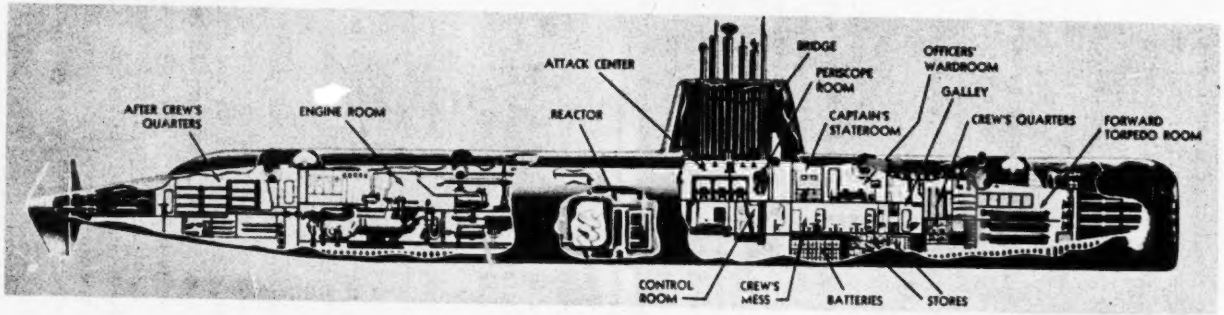

AFTER CREW'S QUARTERS
ENGINE ROOM
REACTOR
ATTACK CENTER
BRIDGE
PERISCOPE ROOM
CAPTAIN'S STATEROOM
OFFICERS' WARDROOM
GALLEY
CREW'S QUARTERS
FORWARD TORPEDO ROOM
CONTROL ROOM
CREW'S MESS
BATTERIES
STORES

Figure 84B. The World War II Nautilus (SS-168)

The reactor compartment contains the nuclear reactor, all steam-generating equipment, and the auxiliary systems. The reactor is located vertically in what would be the forward end of the after battery compartment of a conventional submarine, while the turbines and auxiliary machinery are located in the spaces which were formerly the forward and after enginerooms. In the lower part of the reactor compartment are the primary coolant pumps. Outboard of the pumps is the steam generating equipment. In the upper part of the compartment, above the steam generating equipment is the steam drum (steam separator), from which emerge the main steam lines that lead aft to the engineroom. Aft of the main pumps is the pressurizer unit.

The primary coolant system, located in the reactor compartment, consists of a reactor pressure vessel, which contains the nuclear reactor and coolant loops. The water coolant (primary coolant), which is also the moderator, is circulated by canned-motor-pumps through the reactor to be heated, and then through the steam generators for transfer of heat to the water on the secondary side. Wet steam rises to the steam separator where the water is removed, thus providing dry and saturated steam. The coolant loop is provided with stop valves to permit isolation of parts for maintenance purposes.

From the separator, steam is carried through pipes that penetrate the bulkhead and diverge in the engineroom to supply steam to the propulsion turbine and to the ship's service turbogenerator sets. Condensate is pumped back to the steam generators.

These components constitute the major items of equipment in the reactor compartment. Secondary equipment such as electrical and pneumatic control panels, valves, motor-generator sets, instruments, and related piping and cables constitute the other items located in the reactor compartment.

The engineroom contains the propulsion equipment, all steam-driven items, associated control panels and switch gear, as well as the main control point for the equipment in both submarine compartments. The engineroom is located adjacent to and aft of the reactor compartment. This space is divided into upper and lower levels. Each level is provided with a walkway running fore-and-aft along the horizontal centerline. Components also have to be located on intermediate levels because of their varying size. These intermediate levels are accessible from either the lower or upper level.

b. Primary Coolant System Components

The coolant in a reactor removes heat from the fuel which is undergoing fission. Heated coolant is then circulated through an appropriate type heat exchanger where boiler water is vaporized into steam. Components of the primary coolant system are described below.

Reactor Vessel. --The reactor vessel contains the nuclear core. The submarine thermal reactor is of the conventional pressurized water type and is contained in a pressure vessel of carbon steel which is lined with stainless steel. Thermal insulation in the reactor compartment is conventional in type.

(1) Steam Generators. --The steam generator consists of two vessels, a heat exchanger and a steam drum. The hot primary coolant from the reactor enters the heat exchanger tubes. Surrounding the heat exchanger tubes is the boiler water. Since the primary coolant has a temperature of approximately 500° F, the boiler water (secondary water) starts to boil as the secondary water passes over the radio-active primary coolant. A mixture of steam and water flows up the generating tubes to the steam drum. The water is separated from the steam in the steam drum and returns to the heat exchanger via a number downcomers.

(2) Main Coolant Pumps. --The main coolant pump is of the centrifugal type and is driven by a three-phase induction canned-motor type unit. The complete pump unit consists of an electrical stator assembly, canned-rotor assembly, pressure housing with integral cooler, bearings, pump impeller, and lower boiling ring. The drive unit is assembled into the volute that forms part of the primary loop.

Within the motor, cooled primary water is circulated by means of an auxiliary radial-vane impeller. From the impeller, water flows downward through the "air-gap" to the lower-radial and upper and lower thrust bearings, and into the cooling tubes that form part of the heat exchanger. The water is then brought to the top of the pump where it enters the motor frame and the auxiliary impeller suction. Some water from the auxiliary impeller is bypassed from this circuit to circulate water to the upper radial bearing. The bypassed water flows through the bearing, then directly back to the auxiliary impeller suction.

Motor heat is dissipated to the primary water being recirculated within the pump. A close-fitting labyrinth-type seal on the shaft just below the thrust bearing and a double-spring arrangement prevent the motor cooling water from circulating freely with the high-temperature primary coolant water. Heat from the end turns is transferred by conduction to the pressure shell.

(3) Main Coolant Loop Piping and Valves. --Hydraulically operated stop valves are provided for isolating the primary coolant system. The piping is designed so that thermal expansion stresses are held to acceptable values without expansion joints.

(4) Shielding. --Only the lower level of the reactor compartment is shielded. This permits equipment to be manned while the reactor is operating. Common materials such as lead, iron, water, oil, and plastics are used as shielding in naval reactors. Hydrogen is the most effective atom for stopping fast neutrons. Therefore, for neutron shielding, such materials as water, hydrocarbons, or plastics are about the most effective materials since they all contain hydrogen in their structure. For the reduction of gamma radiation in naval reactors, bulkheads of a heavy material such as lead, are used.

Of necessity, piping and electric cables penetrate the shielding material. The penetrations are watertight and airtight to prevent leak-through of radioactive material.

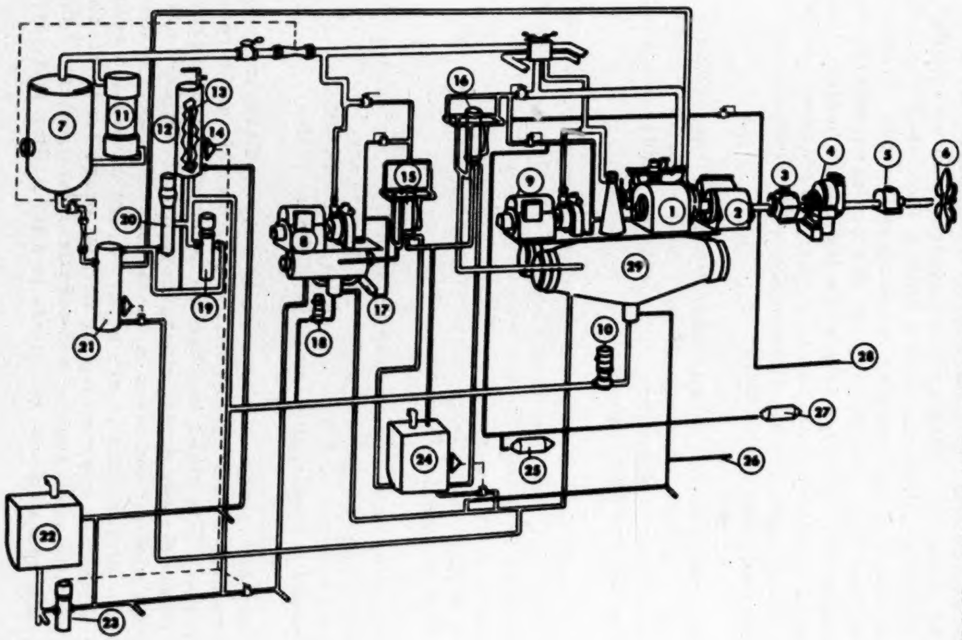
c. Primary Coolant Auxiliary Systems

A considerable number of auxiliary service systems are necessary for proper operation of the primary coolant system.

(1) Charging System. --The system must be filled initially with pure water. There are numerous charging lines to the main loops so that a section that has been isolated for servicing can, by operating the isolating valves, be recharged without a shutdown or risk of sudden loss in pressure. This permits addition of water at any time.

(2) Pressurizing System. --The pressurizing system is designed to maintain a controlled pressure in the primary coolant system and its auxiliary systems under all operating conditions. This system also serves to eliminate surging.

Pressurizing is obtained by electric heaters which provide sufficient heat to build up a head of steam in the pressurizing tank. Since this tank is connected to the primary coolant system, pressure developed in the tank is transmitted to the system.



1—Main turbines
2—Gear
3—Clutch
4—Propulsion motor
5—Thrust bearing
6—Propeller
7—Steam separator
8—Coolant pump t-g set
9—Ship's service t-g set
10—Main condensate pump
11—Stand-by condenser
12—Surge tank
13—Overflow
14—Lo level control
15—Air ejector
16—Main air ejector
17—Lube-oil cooler
18—Condensate pump
19—Main boiler-feed pump
20—Auxiliary boiler-feed pump
21—Feed heater
22—Feed storage tank
23—Feed distribution pump
24—Drain collecting tank
25—Main lube-oil cooler
26—From 4000-gpd evaporator
27—Shaft lube-oil cooler
28—To 4000-gpd evaporator
29—Main condenser

Courtesy of Westinghouse Electric Corp.

Figure 85. Schematic of the Nautilus Engineroom Showing Steam and Condensate Systems

172. STEAM PLANT

The primary purpose of the boat's steam plant is to convert the heat energy developed by the reactor into useful shaft horsepower for propulsion. In addition, the steam plant also supplies power to all auxiliaries for power-plant operation, plus all electrical equipment and lighting systems, and providing sufficient power for charging the battery.

The steam plant aboard a nuclear powered submarine is patterned after a conventional shipboard installation insofar as the handling of the steam and condensate is concerned. In view of the fact that the hull of a submarine is of a limited size, it is impossible to include a deaerating feed tank in the steam system. Instead of the deaerating feed tank, the steam plant of a nuclear powered submarine is equipped with a surge tank and a feed water heater. The steam system is subdivided into identical port and starboard system plants which can be operated simultaneously, either cross-connected, or isolated from each other.

The main engines are geared, marine-type steam turbines. There are auxiliary power turbogenerators with associated equipment such as auxiliary condensers, air ejectors, condensate pumps, and lubricating oil systems (fig. 85).

Since every 33 feet of sea water is equal to the pressure of 1 atmosphere (14.7 psi), the circulating water systems was designed for high pressures to contain the sea water for static conditions corresponding to maximum submergence. In addition, equipment was designed to provide for large heat-transfer surface and high flows necessary for disposal of waste heat.

To convert the shaft horsepower from the low- and high-pressure turbines into useful thrust, the torque passes through the reduction gears, a clutch, and finally through the propulsion motor shaft. The power is then applied directly to the propeller.

The propulsion system clutch enables the propulsion motor and propeller section to be disengaged from the turbine and main reduction-gear section. This clutch mechanism is incorporated to provide for running on the diesels during emergency. If a clutch were not used, the propulsion motor, when in operation, would have to overcome the inertia and friction losses of the turbine rotors and reduction gear in addition to overcoming the normal propeller load. The clutch also permits some angular and parallel misalignment of the drive shaft. Incorporated with the clutch is a thrust link that serves to locate the reduction gears axially and transmit any axial forces due to these gears to the main thrust bearing.

Control panels are provided in the maneuvering room for operational control of the plant. The propulsion panel has all of the controls necessary for operating the main shaft. These include the speed controls for the turbine and propulsion motor.

173. MANEUVERABILITY

A submarine must be highly maneuverable. For nuclear powered submersibles this means that the power plant must be capable of varying propulsion output rapidly from normal cruising to full power ahead. The U. S. N. nuclear powered submarines handle efficiently and with ease during dives, climbs, and turns.

Nuclear powered submarine power plants are designed to function in three ways: normal operation, i.e., propulsion by the main geared turbines, with steam furnished by the reactor system; or emergency operation, by either the diesel generator, or the electric-motor drives from power supplied by batteries. The batteries needed are smaller and fewer than on any conventional submarine. This provides additional space aboard the boat.

Both the diesel and battery systems are in operating condition and can be utilized at a moment's notice by merely switching one or the other on through the maneuvering panel.

174. ADVANTAGES OF NUCLEAR PROPULSION

That atomic reactors can be substituted for boilers burning conventional fuels was recognized as soon as it became clear that self-sustaining chain reactions could be brought about. We have seen that the first large atomic power producing installations in the United States for naval propulsion systems were built for the Nautilus and Seawolf. These two boats have been in operational status for a long enough period that it becomes possible to begin to examine the advantages of nuclear propulsion.

It is obvious that a major advantage of nuclear power for any naval vessel is in logistics. The cruising range and strategic value of a warship have heretofore been limited by the amount of fuel that could be stored in a ship's hull. When its fuel is depleted, a conventional ship must turn to a fueling ship or a fueling station. Refueling operations are time consuming, hazardous, and reduce a ship's effectiveness. During World War II, the Navy succeeded in operating mobile refueling bases which were able to follow task forces. The striking power of the Fleet was thus extended, but only by providing the Fleet with an endless chain of tankers.

Nuclear-powered ships will have virtually unlimited cruising range, even at high speeds. No refueling facilities will be required to replenish their propulsion fuel. This will be done routinely as part of a regular, scheduled overhaul. Consequently, the construction and overhaul facilities heretofore required to service the tankers and their equipment will be reduced. Also, fewer escort vessels will be needed to protect the remaining tankers. Personnel now assigned to man such Fleet support ships and their shore facilities will be released for other purposes. All of this will result in less drain on our manpower during wartime--and manpower is the factor which ultimately limits a nation's war potential.

For example, the Nautilus, after more than two years of operation, is already operating on her second fuel load--having been refueled in April 1957. The aim is to design naval nuclear power plants which can last for an entire war without being refueled.

On her first nuclear fuel load, the Nautilus steamed 62,562 miles, more than half of this distance fully submerged. For a conventional surface ship to steam such distance, it would require more than 2 million gallons of fuel oil. From a logistics point of view, 2 million gallons of fuel oil represents a train of tank cars 1 1/2 miles long. Recently the Nautilus steamed, fully submerged, from New London, Connecticut, to San Diego, California, a distance of 3049 miles. She surfaced only long enough to pass through the Panama Canal.

Another advantage of nuclear power is that the fuel requires no oxygen. For the first time the Navy is not dependent upon the earth's atmosphere for the combustion of fuel. The significance of this can be understood when it is realized that a large vessel consumes 600,000 cubic feet, or 20 tons, of air to burn the more than 1 ton of fuel oil required each minute at full power.

In a conventional ship, ducts lead air to the boiler furnace. Other ducts and stacks remove the gases of combustion. Altogether, these ducts take up a great deal of volume on the upper deck levels, space which could be used for other purposes in nuclear-powered ships; and the danger exists that the rupture of exhaust ducting during battle can spread fumes throughout the working area below decks.

For aircraft carriers nuclear power offers additional advantages. Space now used for fuel oil can be used to carry large quantities of aviation fuel, ammunition, and other supplies. The carrier will thus be able to support many more hours of aircraft flight, and its military capabilities correspondingly increased. Also, stack gases are a fume hazard to personnel and to the handling and operating of aircraft on the flight deck. With nuclear power these hazards are eliminated and better arrangement of the upper decks for aircraft operation is made possible.

Think what the use of nuclear fuel will mean from a storage standpoint. The Navy will be able to store the replacement fuel required for all of the Navy's nuclear powered vessels in a few large buildings. Nuclear fuel is not radioactive and it does not deteriorate. It can be manufactured and stored indefinitely during peacetime. Should the fuel not be required for naval purposes, it could be converted to use in shore-based atomic power plants.

175. PERSONNEL SAFETY

Although personnel safety is a factor to consider in operating a steam power plant within a submarine, of more urgent concern is positive protection from nuclear radiation.

The shield reduces the radiation to a level such that, during a cruise lasting the life of the reactor, the average crew member will receive less radiation than he would during a lifetime from cosmic rays, routine chest and dental X-rays, television screens, etc.

The radiation-monitoring system for a nuclear powered submarine is to ensure proper radiation levels for personnel protection. The system includes air-particle detectors, gamma detectors, boiler-leak detectors, and a discharge system activity indicator. The air detectors sample the radioactivity of the air in the shielded area and in adjacent compartments. Gamma detectors are installed in various sections of the boat. The boiler-leak detectors warn of a ruptured boiler tube in the steam generator, which would allow radioactive coolant to enter the unshielded steam system. The discharge system-activity indicators ensure that radioactive water is not discharged at a dock or elsewhere where it would produce hazardous conditions.

APPENDIX I

SYMBOLS

SYMBOL	MEANING	SPELLED	PRONOUNCED
A	Mass number		
Z	Atomic number		
α, $_2\alpha^4$,	Alpha particle Helium nucleus		
β^-, $_{-1}\beta^0$	Beta particle		
β^+, $_{+1}\beta^0$	Positive beta particle Positron		
γ, $_0\gamma^0$	Gamma radiation		
λ	Wavelength	Lambda	lăm'da
ν	Frequency	Nu	nū
η, $_0\eta^0$	Neutrino	Eta	ēta
h	Planck's constant		
k	Boltzmann's constant		
R	Rydberg's constant		
ρ	Density	Rho	rō
σ	Cross section	Sigma	sĭg'ma
ν	Neutrons per fission	Nu	nū
f	Productivity factor		
k	Multiplication or reproduction factor		

SYMBOL	MEANING	SPELLED	PRONOUNCED
M	Multiplication		
m_e	Mass of electron		
n	Neutron		

APPENDIX II

VALUES OF PHYSICAL CONSTANTS

CONSTANT	SYMBOL AND VALUE
Atomic mass unit	Amu $= 1.67 \times 10^{-24}$ g = 931 Mev
Avogadro's number	$N = 6.02 \times 10^{23}$ molecules/gram mol. wt.
Velocity of light	$c = 3 \times 10^{10}$ cm/sec
Boltzmann's constant	$k = 1.38 \times 10^{-16}$ erg/deg K.
Charge on the electron	$e = 4.803 \times 10^{-10}$ esu
Planck's constant	$h = 6.625 \times 10^{-27}$ erg-sec
Rydberg's constant	$R = 109737$ cm^{-1}
Base of natural logarithms	$e = 2.7183$
Electron rest mass	$m_e = 9.1 \times 10^{-28}$ g; 0.00055 amu
Proton rest mass	$m_p = 1.66 \times 10^{-24}$ g; 1.00758 amu
Neutron rest mass	$m_n = 1.67 \times 10^{-24}$ g; 1.00894 amu
Absolute zero	$= -273.16^{\circ}$ C.; 0° K.

APPENDIX III

USEFUL CONVERSIONS

LENGTH

1 cm = 0.394 in = 10 mm

1 in = 2.54 cm

1 meter = 100 cm = 10^6 microns = 39.37 in

1 micron = 10^{-4} cm

1 angstrom unit = 10^{-8} cm

AREA

1 cm^2 = 0.155 in^2

1 barn = 1×10^{-24} cm^2

VOLUME

1 cm^3 = 0.061 in^3

1 liter = 1000 cm^3

TIME

1 sec = 10^6 microseconds

MASS

1 kg = 2.2 lbs

1 lb = 453.6 g

PRESSURE

1 atm = 1033.2 g/cm^2 = 14.7 lb/in^2

WORK AND ENERGY

1 erg = 1 dyne-cm = 1×10^{-7} joule = 2.39×10^{-8} cal

1 joule = 10^{7} erg = 2.778×10^{-4} watt hours

1 ev = 1.6×10^{-12} erg

1 amu = 931 Mev

MISCELLANEOUS

1 curie = 3.7×10^{10} disintegrations/sec

APPENDIX IV

TABLE OF ATOMIC MASSES

Z	ELEMENT	A	MASS
0	Electron	0	0.00055
0	Neutron	1	1.00894
1	Proton	1	1.00758
1	Hydrogen	1	1.00813
	(Deuterium)	2	2.01471
	(Tritium)	3	3.01702
2	Helium	3	3.01700
		4	4.00390
		6	6.0209
3	Lithium	6	6.01697
		7	7.01822
		8	8.02502
4	Beryllium	7	7.01916
		9	9.01503
		10	10.01677
5	Boron	9	9.01620
		10	10.01618
		11	11.01284
		12	12.0190
6	Carbon	10	10.02100
		11	11.01495
		12	12.00382
		13	13.00751
		14	14.00767
7	Nitrogen	13	13.00988
		14	14.00751
		15	15.00489
		16	16.00688
8	Oxygen	15	15.0078
		16	16.000000
		17	17.00450
		18	18.00490
		19	19.0139
9	Fluorine	17	17.0075
		18	18.0065
		19	19.00450
		20	20.0067
10	Neon	19	19.00781
		20	19.99877
		21	20.99963
		22	21.99844
		23	22.0013
11	Sodium	21	21.0035
		22	21.9999

Z	ELEMENT	A	MASS
19	Potassium	37	36.9830
		38	37.9795
		39	38.9747
		40	39.9760
		41	40.9739
20	Calcium	40	39.9753
		42	41.9711
		43	42.9723
		45	44.968
21	Scandium	45	44.9669
		46	45.96909
22	Titanium	46	45.9661
		47	46.9647
		48	47.9631
		49	48.9646
		50	49.9621
		51	50.9587
23	Vanadium	51	50.9577
		52	51.95857
24	Chromium	51	50.958
		52	51.956
		53	52.956
		54	53.960
25	Manganese	55	54.957
26	Iron	54	53.957
		56	55.9568
		57	56.957
27	Cobalt	59	58.94
28	Nickel	58	57.9594
		60	59.9495
		61	60.9537
		62	61.9493
		64	63.9471
29	Copper	63	62.957
		64	63.955
		65	64.955
30	Zinc	64	63.954
		66	65.954
		67	66.954
		68	67.955
		70	69.954
31	Gallium	69	68.952
		71	70.952
32	Germanium		
33	Arsenic	75	74.934

Z	ELEMENT	A	MASS
		122	121.945
		124	123.944
51	Antimony		
52	Tellurium	126	125.937
		128	127.936
53	Iodine	127	126.933
54	Xenon	129	128.946
		132	131.946
55	Caesium		
56	Barium	138	137.916
57	Lanthanum	139	138.953
58	Cerium		
59	Praseodymium		
60	Neodymium	145	144.962
		146	145.962
		148	147.962
		150	149.964
61	Promethium		
62	Samarium		
63	Europium		
64	Gadolinium	154	153.971
		155	154.971
		156	155.972
		157	156.973
		158	157.973
		160	159.974
65	Terbium		
66	Dysprosium		
67	Holmium	165	164.98
68	Erbium		
69	Thulium		
70	Ytterbium		
71	Lutetium		174.99
72	Hafnium		
73	Tantalum	181	180.928
74	Tungsten	184	184.00
75	Rhenium	187	186.981
76	Osmium	189	189.04
		190	190.030
		192	192.04
77	Iridium	191	191.040
		193	193.040
78	Platinum	194	194.039
		195	195.039
		196	196.039

Z	ELEMENT	A	MASS
		23	22.99618
		24	23.9975
		25	24.9967
12	Magnesium	23	23.0002
		24	23.9925
		25	24.9938
		26	25.9898
		27	26.9928
13	Aluminum	25	24.9981
		26	25.9929
		27	26.9899
		28	27.9903
		29	28.9893
14	Silicon	27	26.9949
		28	27.9866
		29	28.9866
		30	29.9832
		31	30.9862
15	Phosphorus	29	28.9919
		30	29.9873
		31	30.9843
		32	31.9827
		33	32.9826
		34	33.9826
16	Sulphur	31	30.9899
		32	31.98089
		33	32.9800
		34	33.97710
		35	34.9788
		36	35.978
		37	36.9821
17	Chlorine	33	32.9860
		34	33.9801
		35	34.97867
		36	35.9780
		37	36.97750
		38	37.981
		39	38.9794
18	Argon	35	34.9850
		36	35.9780
		37	36.9777
		38	37.974
		39	38.9755
		40	39.9756
		41	40.9770

Z	ELEMENT	A	MASS
34	Selenium	78	77.938
		80	79.942
35	Bromine	79	78.929
		81	80.930
36	Krypton	78	77.945
		82	81.939
		84	83.938
		86	85.939
37	Rubidium		
38	Strontium		
39	Yttrium		
40	Zirconium		
41	Niobium	93	92.926
42	Molybdenum	94	93.945
		95	94.946
		96	95.944
		97	96.945
		98	97.943
		100	99.945
43	Technetium		
44	Ruthenium	96	95.945
		98	97.943
		99	98.944
		100	99.942
		101	100.946
		102	101.941
45	Rhodium	103	102.941
46	Palladium	102	101.941
		104	103.941
		105	104.942
		106	105.941
		108	107.941
		110	109.941
47	Silver	107	106.945
		108	107.947
		109	108.944
48	Cadmium		
49	Indium		
50	Tin	115	114.940
		116	115.939
		117	116.937
		118	117.937
		119	118.938
		120	119.937

Z	ELEMENT	A	MASS
		198	198.090
79	Gold	197	197.039
80	Mercury	200	200.028
81	Thallium	203	203.050
		205	205.050
82	Lead	204	204.050
		206	206.050
		207	207.050
		208	208.050
83	Bismuth	209	209.050
84	Polonium		
85	Astatine		
86	Radon		
87	Francium		
88	Radium	226	226.10
89	Actinium		
90	Thorium	232	232.12
		234	234.1121
91	Protactinium		
92	Uranium	235	235.1133
		238	238.1204
93	Neptunium	234	234.1119*
		235	235.1137*
		236	236.1156*
		237	237.1176*
		238	238.1199*
		239	239.1222*
94	Plutonium	238	238.1197*
		239	239.1228*
95	Americium	241	241.1269*
96	Curium	240	240.1259*
		242	242.1293*
97	Berkelium		
98	Californium		

* Weights calculated by means of the atomic mass equation – not observed experimentally.

APPENDIX V

GENERAL ELECTRIC CHART OF THE NUCLIDES

All the necessary information for the use of this chart appears in the upper left corner of the rear of the chart. We shall note some of the more important items.

Each of the horizontal rows represents one element. The spaces in each row that are filled show the known isotopes of the element. Spaces shaded in gray represent isotopes which occur in nature and generally are considered stable. Actually, a few of these "stable" nuclides are radioactive but of very long half life; these are indicated by black rectangular areas within their spaces. The unshaded spaces represent radioactive isotopes; those with black rectangular areas show they are found in nature.

The space at the left end of each row, heavily bordered in black, gives properties of each element as a whole, including the chemical atomic weight.

In each of the other occupied spaces, there is shown first the symbol, followed by the mass number of the nuclide indicated. The mass number, A, is the number of nucleons in the nucleus. A-Z is thus the number of neutrons. This number is listed at the bottom of alternate columns.

Isobars lie in spaces placed diagonally from lower right to upper left.

For stable nuclei, abundance of the isotope is given. For radioactive nuclei, the emission, percentage of the various radiations, and their energies and half lives, are presented. A "Classification" letter appears before the symbol for each nuclide. The classification code appears under the column labeled "symbols." Some of the known isomeric states are indicated by a division of the space for the nuclide. Thermal neutron absorption cross sections are listed in ovals in nuclide spaces when such information is known and unclassified. A small black triangle in the lower right on a nuclide space indicates that this particular isotope may be a fission fragment.

Included on the back of the chart is coding for nuclear reactions. If the nuclear reaction and original nucleus is known, the product nucleus may be found. Displacements caused by nuclear reactions are also coded on the back of the chart.

APPENDIX VI

THE ELEMENTS

NAME	SYMBOL	ATOMIC NO.
Actinium	Ac	89
Aluminum	Al	13
Americium	Am	95
Antimony	Sb	51
Argon	A	18
Arsenic	As	33
Astatine	At	85
Barium	Ba	56
Berkelium	Bk	97
Beryllium	Be	4
Bismuth	Bi	83
Boron	B	5
Bromine	Br	35
Cadmium	Cd	48
Calcium	Ca	20
Californium	Cf	98
Carbon	C	6
Cerium	Ce	58

NAME	SYMBOL	ATOMIC NO.
Cesium	Cs	55
Chlorine	Cl	17
Chromium	Cr	24
Cobalt	Co	27
Copper	Cu	29
Curium	Cm	96
Dysprosium	Dy	66
Erbium	Er	68
Europium	Eu	63
Fluorine	F	9
Francium	Fr	87
Gadolinium	Gd	64
Gallium	Ga	31
Germanium	Be	32
Gold	Au	79
Hafnium	Hf	72
Helium	He	2
Holmium	Ho	67
Hydrogen	H	1
Indium	In	49
Iodine	I	53
Iridium	Ir	77

NAME	SYMBOL	ATOMIC NO.
Iron	Fe	26
Krypton	Kr	36
Lanthanum	La	57
Lead	Pb	82
Lithium	Li	3
Lutetium	Lu	71
Magnesium	Mg	12
Maganese	Mn	25
Mercury	Hg	80
Molybdenum	Mo	42
Neodymium	Nd	60
Neon	Ne	10
Neptunium	Np	93
Nickel	Ni	28
Niobium (Columbium)	Nb (Cb)	41
Nitrogen	N	7
Osmium	Os	76
Oxygen	O	8
Palladium	Pd	46
Phosphorus	P	15
Platinum	Pt	78
Plutonium	Pu	94

NAME	SYMBOL	ATOMIC NO.
Polonium	Po	84
Potassium	K	19
Praseodymium	Pr	59
Promethium	Pm	61
Protactinium	Pa	91
Radium	Ra	88
Radon (Emanation)	Rm (EM)	86
Rhenium	Re	75
Rhodium	Rh	45
Rubidium	Rb	37
Ruthenium	Ru	44
Samarium	Sm	62
Scandium	Sc	21
Selenium	Se	34
Silicon	Si	14
Silver	Ag	47
Sodium	Na	11
Strontium	Sr	38
Sulfur	S	16
Tantalum	Ta	73
Technetium	Tc	43
Tellurium	Te	52

NAME	SYMBOL	ATOMIC NO.
Terbium	Tb	65
Thallium	Tl	81
Thorium	Th	90
Thulium	Tm	69
Tin	Sn	50
Titanium	Ti	22
Tungsten	W	74
Uranium	U	92
Vanadium	V	23
Xenon	Xe	54
Ytterbium	Yb	70
Yttrium	Y	39
Zinc	Zn	30
Zirconium	Zr	40

APPENDIX VII
GLOSSARY

Absolute Zero--The temperature at which all thermal (molecular) motion ceases; zero point in the absolute temperature scale, equal to -273.18° C. or -459.72° F. Absolute temperature T is given by the equation:

$$1/2\ mv_{av}^2 = 3/2\ kT.$$

Absorption--
1. The internal taking up of one material by another.
2. Transformation of radiant energy into other forms of energy when passing through a material substance.

Absorption Coefficient--The fractional decrease in intensity of a beam of radiation per unit thickness (linear absorption coefficient), per unit volume (mass absorption coefficient), or per atom (atomic absorption coefficient) of absorber.

Acceleration--The time rate of change of velocity in either magnitude or direction. CGS unit: cm/sec^2.

Acceleration Due to Gravity (g)--The acceleration of a freely falling body in a vacuum; 980.665 cm/sec^2 or 32.174 ft/sec^2 at sea level and 45° latitude.

Activation Energy--The energy necessary to start a particular reaction. Nuclear: The amount of outside energy which must be added to a nucleus to start a particular nuclear reaction. Chemical: The amount of outside energy necessary to activate an atom or molecule to cause it to react chemically.

Absorption--The adhesion of one substance to the surface of another.

Alpha Particle--A helium nucleus, consisting of 2 protons and 2 neutrons, with a double positive charge. Its mass is 4.002764 amu (mass units).

Alpha Ray--A stream of fast-moving helium nuclei; a strongly ionizing and weakly penetrating radiation.

Alternating Current--An electric current (flow of electrons) which periodically reverses direction.

Ampere--The practical unit of current; that current which will deposit 0.001118 gm of silver in 1 sec; the flow of 1 coulomb/sec; the flow of 3×10^{19} electrons/second. Abbreviation: amp.

Amplification--As related to detection instruments, the process (either gas, electronic, or both) by which ionization effects are magnified to a degree suitable for their measurement.

Amplitude--The maximum value of the displacement in an oscillatory motion.

Angular Acceleration--The time rate of change of angular velocity either in angular speed or in the direction of the axis of rotation. CGS unit: radians/sec^2.

Angular Velocity--The time rate of angular displacement about an axis. CGS unit: radians/sec. If the angle described in time t is θ, the angular velocity is $\omega = \frac{\theta}{t}$, where θ is in radians, t is in seconds, and ω is in radians per second.

Angstrom Unit--10^{-8} cm, a convenient unit for measuring wavelength of light. Abbreviation: Å.

Atom--The smallest particle of an element which still retains all characteristics of the element.

Atomic Number--The number of protons in the nucleus, hence the number of positive charges on the nucleus. It is also the number of electrons outside the nucleus of a neutral atom. Symbol: Z.

Atomic Weight--The relative weight of the atom of an element compared with the weight of one atom of oxygen taken as 16; hence, a multiple of 1/16 the weight of an atom of oxygen.

Avogadro's Law--The hypothesis that equal volumes of all gases at the same pressure and temperature contain equal numbers of molecules. Hence the number of molecules contained in 1 cm^3 of any gas under standard conditions is a universal constant.

Avogadro's Number--The number of molecules in a gram-molecular weight of any substance (6. 03 x 10^{23} molecules); also, the number of atoms in a gram-atomic weight of any element.

Barn--The unit expressing the probability of a specific nuclear reaction taking place in terms of cross-sectional area. It is 10^{-24} cm^2. (See Cross Section.)

Beta Particle--A charged particle emitted from the nucleus and having a mass and charge equal in magnitude to those of the electron.

Beta Ray--A stream of beta particles, more penetrating but less ionizing than alpha rays; a stream of high-speed electrons.

Binding Energy--The energy represented by the difference in mass between the sum of the component parts and the actual mass of the nucleus.

Brownian Movement--The continuous agitation of the particles of a colloidal suspension caused by the thermal motion of the molecules of the surrounding medium.

Calorie--The amount of heat necessary to raise the temperature of 1 gm of water 1° C. (from 14. 5° C. to 15. 5° C.). Abbreviation: cal.

Centripetal Force--The force required to keep a moving mass traveling in a circular path. The force is directed toward the axis of the circular path.

Chain Reaction--Any chemical or nuclear process in which some of the products of the process are instrumental in the continuation or magnification of the process.

Chemical Compound--A pure substance composed of two or more elements combined in a fixed and definite proportion by weight.

Conservation of Energy--The principle that energy can neither be created nor destroyed, and therefore the total amount of energy in the universe is constant. This law of classical physics is modified for certain nuclear reactions. (See Conservation of Mass-Energy.)

Conservation of Mass-Energy--The principle that energy and mass are interchangeable in accordance with the equation $E = mc^2$; where E is energy, m is mass, and c is velocity of light.

Coulomb's Law of Electrostatic Charges--The force of attraction or repulsion exerted between two electrostatic charges, Q_1 and Q_2, a distance, s, apart separated by a medium of dielectric value, ϵ, is given by the equation:

$$F = \frac{Q_1 Q_2}{\epsilon s^2}.$$

Critical Size--For fissionable material, the minimum amount of a material which will support a chain reaction.

Cross Section (Nuclear)--The area subtended by an atom or molecule for the probability of a reaction; that is, the reaction probability measured in units of area.

Decay--The disintegration of the nucleus of an unstable element by the spontaneous emission of charged particles and/or photons.

Density--The mass per unit volume. CGS unit: gm/cm^3.

Deuterium--A heavy isotope of hydrogen having 1 proton and 1 neutron in the nucleus. Symbol: D or ${}_1H^2$.

Deuteron--The nucleus of a deuterium atom containing 1 proton and 1 neutron.

Dyne--That unit of force which, when acting upon a mass of 1 gm, will produce an acceleration of 1 cm/sec^2.

Electric Field Intensity--The magnitude of the intensity of an electric field at a particular point, equal to the force which would be exerted upon a unit positive charge placed in the field at that point. The direction of the electric field is the direction of this force.

Electron--A negatively charged particle which is a constituent of every atom. A unit of negative electricity equal to 4.80×10^{-10} esu. Its mass is 0.000548 mu.

Electron Volt--The amount of energy gained by an electron in passing through a potential difference of 1 volt. 1 ev = 1.6×10^{-12} ergs. Abbreviation: ev.

Electrostatic Field--The region surrounding an electric charge in which another electric charge experiences a force.

Electrostatic Unit of Charge (Statcoulomb)--That quantity of electric charge which, when placed in a vacuum 1 cm distant from an equal and like charge, will repel it with a force of 1 dyne. Abbreviation: esu.

Element--A pure substance consisting of atoms of the same atomic number, which cannot be subdivided by ordinary chemical means.

Endoergic Reaction--A reaction which absorbs energy.

Energy--The capacity for doing work. Potential energy is the energy inherent in a body because of its position with reference to other bodies. Kinetic energy is the energy possessed by a mass because of its motion. CGS units: gm-cm^2/sec^2, or erg.

Erg--The unit of work done by a force of 1 dyne acting through a distance of 1 cm. The unit of energy which can exert a force of 1 dyne through a distance of 1 cm. CGS units: dyne-cm, or gm-cm^2/sec^2.

Exoergic Reaction--The reaction which liberates energy.

Fission. See Nuclear Fission.

Fission Products--The elements and/or particles produced by fission.

Force--The push or pull which tends to impart motion to a body at rest, or to increase or diminish the speed or change the direction of a body already in motion.

Frequency--The number of cycles, revolutions, or vibrations completed in a unit of time. CGS unit: sec^{-1}.

Fusion. See Nuclear Fusion.

Gamma Ray--A high-frequency electromagnetic radiation with a range of wavelength from 10^{-9} to 10^{-10} cm, emitted from the nucleus.

Gram-Atomic Weight--The relative atomic weight of an element, expressed in grams.

Gram-Molecular Weight (Gram-Mole)--The relative molecular weight of a compound, expressed in grams.

Half Life--The time required for one-half of the atoms of the substance originally present to decay by radioactivity.

Half Thickness--The thickness of absorbing material necessary to reduce the intensity of radiation by one-half.

Heat--The energy associated with a mass because of the random motions of its molecules.

Heavy Water--The popular name for water which is composed of 2 atoms of deuterium and 1 atom of oxygen.

Hydrogen Atom--The atom of lightest mass and simplest atomic and nuclear structure, consisting of 1 proton with 1 orbital electron. Its mass is 1.008123 mu.

Intensity of Radiation--The amount of radiant energy emitted in a specified direction per unit time and per unit surface area.

Ion--An atomic particle, atom, or chemical radical (group of chemically combined atoms) bearing an electrical charge, either positive or negative, caused by an excess or deficiency of electrons.

Ionization--The act or result of any process by which a neutral atom or molecule acquires either a positive or a negative charge.

Ionization Potential--The potential necessary to separate 1 electron from an atom with the formation of an ion having 1 elementary charge.

Ionizing Event--An event in which an ion is produced.

Isobars--Elements having the same mass number but different atomic numbers.

Isotope--One of two or more forms of an element having the same atomic number (nuclear charge) and hence occupying the same position in the periodic table. All isotopes are identical in chemical behavior, but are distinguishable by small differences in atomic weight. The nuclei of all isotopes of a given element have the same number of protons but have different numbers of neutrons.

Joule--A unit of work or energy. 1 joule = 10^7 ergs.

Kinetic Energy--The energy which a body possesses by virtue of its mass and velocity. The equation is: $K. E. = 1/2\ mv^2$.

Mass--The quantity of matter. One of the fundamental dimensions.

Mass Number--The number of nucleons in the nucleus of an atom. Symbol: A.

Mass Unit--A unit of mass based upon 1/16 the weight of an oxygen atom taken as 16.00000. Abbreviation: mu, or atomic mass unit, amu.

Mean Free Path--The average distance a particle moves between collisions. Abbreviation: mfp, symbol, $\bar{l}$.

Meson--A short-lived particle carrying a positive, negative, or zero charge, and having a variable mass in multiples of the mass of the electron. Also called mesotron.

Metastable State--An excited state of a nucleus which returns to the ground state by the emission of a gamma ray over a measurable half life.

Mev--The abbreviation for million electron volts. See Electron Volt.

Molecule--The ultimate unit quantity of a compound which can exist by itself and retain all the properties of the original substance.

Molecular Weight--The sum of the atomic weights of all the atoms in a molecule.

Momentum--The product of the mass of a body and its velocity. CGS unit: gm-cm/sec.

Neutron--An elementary nuclear particle with a mass approximately the same as that of a hydrogen atom and electrically neutral; a constituent of the atomic nucleus. Its mass is 1.00893 mu.

Neutrino--A particle with zero rest mass and zero charge, emitted to preserve spin, momentum, and energy in β decay and other processes.

Nuclear Fission--A special type of nuclear transformation characterized by the splitting of a nucleus into at least two other nuclei and the release of a relatively large amount of energy.

Nuclear Fusion--The act of coalescing two or more nuclei.

Nucleon--The common name for the constituent parts of the nucleus. At present applied to protons and neutrons, but will include any other particle that is found to exist in the nucleus.

Nucleus--The heavy central part of an atom in which most of the mass and the total positive electric charge are concentrated. The charge of the nucleus, an integral multiple Z of the charge of the proton, is the essential factor which distinguishes one element from another. Z is the atomic number.

Nuclide--A general term referring to all nuclear species--both stable (about 270) and unstable (about 500)--of the chemical elements, as distinguished from the two or more nuclear species of a single chemical element which are called isotopes.

Packing Fraction--The difference between the atomic weight in mass units and the mass number of an element divided by the mass number and multiplied by 10,000. It indicates nuclear stability. The smaller the packing fraction, the more stable the element.

Photoelectric Effect--The process by which a photon ejects an electron from its atom. All the energy of the photon is absorbed in ejecting the electron and in imparting kinetic energy to it.

Photon--A quantity of energy emitted in the form of electromagnetic radiation whose value is the product of its frequency and Planck's constant. The equation is: $E = h\nu$.

Planck's Constant--A natural constant of proportionality h relating the frequency of a quantum of energy to the total energy of the quantum;

$$h = \frac{E}{\nu} = 6.6 \times 10^{-27} \text{ erg-sec.}$$

Positron--A nuclear particle equal in mass to the electron and having an equal but opposite charge. Its mass is 0.000548 mu.

Potential Difference--The difference in potential between any two points in a circuit; the work required to carry a unit positive charge from one point to another.

Power--The time rate of doing work; the time rate of expenditure of energy.

Pressure-The perpendicular component of force applied to a unit area; the total force divided by total area. CGS unit: dyne/cm^2.

Primary Electron--The electron ejected from an atom by an initial ionizing event, as caused by a photon or beta particle.

Principal Quantum Number--The number, n = 1, 2, 3, . . . which describes the basic state of an atomic system in quantum theory.

Proton--A nuclear particle with a positive electric charge equal numerically to the charge of the electron and having a mass of 1.007575 mu.

Quantum--A discrete quantity of radiative energy equal to the product of its frequency and Planck's constant. The equation is: $E = h\nu$.

Quantum Level--An energy level of an electron or of any atomic system, distinct from any other of its energy levels by discrete quantities dependent upon Planck's constant.

Quantum Mechanics--The science of description of atomic systems in terms of discrete quantum states.

Quantum Number--One of a set of integral or half-integral numbers, one for each degree of freedom, which determines the state of an atomic system in terms of the constants of nature.

Quantum State--A term defining the way in which an atomic system exists at any specific time. This state is often described by means of a complex mathematical function. See Quantum Level.

Quantum Theory--The concept that energy is radiated intermittently in units of definite magnitude called quanta.

Radiation--A method of transmission of energy. Specifically:

1. Any electromagnetic wave (quantum).
2. Any moving electron or nuclear particle, charged or uncharged, emitted by a radioactive substance.

Radioactivity--The process whereby certain nuclides undergo spontaneous atomic disintegration in which energy is liberated, generally resulting in the formation of new nuclides. The process is accompanied by the emission of one or more types of radiation, such as alpha particles, beta particles, and gamma radiation.

Reaction--Any process involving a chemical or nuclear change.

Roentgen--The quantity of X or γ radiation which produces 1 esu of positive or negative electricity/cm^3 of air at standard temperature and pressure or 2.083×10^9 ion pairs/cm^3 of dry air.

Speed--The time rate of displacement; distance moved per unit time. CGS unit: cm/sec.

Spin--The inherent, intrinsic angular momentum of an atomic particle; a quantum number in modern atomic theory.

Temperature--A measure of the degree of heat, or the intensity of heating, of an object.

Valence--The number representing the combining or displacing power of an atom; number of electrons lost, gained, or shared by an atom in a compound; the number of hydrogen atoms with which an atom will combine, or the number it will displace.

Valence Electron--Any electron which is gained, lost, or shared in a chemical reaction. Usually valence electrons are the outermost electrons in the atom.

Velocity--The time rate of displacement in a fixed direction. CGS unit: cm/sec.

Velocity of a Wave--The velocity of propagation in terms of wavelength λ and period T, or frequency ν. The equation is:

$$v = \frac{\lambda}{T} = \nu\lambda.$$

Wavelength--The linear distance between any two similar points of two consecutive waves.

Wave Motion--The progressive disturbance propagated in a medium by periodic vibration of the particles of the medium. Transverse wave motion is that in which the vibration of the particles is perpendicular to the direction of propagation. Longitudinal wave motion is that in which the vibration of the particles is parallel to the direction of propagation.

Weight--The force with which a body is attracted toward the earth. CGS units: gm-cm/sec^2.

Work--The transfer of energy by the application of a force through a distance. Product of a force and the distance through which it moves. CGS units: gm-cm^2/sec^2.

APPENDIX VIII

ANSWERS TO PROBLEMS

Paragraph 3e

(1) $T = \frac{2E}{3k}$

(2) $V = \sqrt{\frac{2E}{m}}$

(3) $T = \frac{mv^2}{3k}$

(4) 3

(5) $\frac{c-b}{a}$

Paragraph 10

a. 1215

b. 6950

c. 0.0161

d. 15.6

e. 162.3

f. 1730

g. 52.6

h. 6.05

i. 0.00744

Paragraph 10 (cont'd)

j. 53.0

k. 60.3

l. 0.0166

m. 0.887

o. 0.000139

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Paragraph 18

a. 4.9×10^4 dynes

b. 1.43×10^3 cm/sec^2

c. 30 cm/sec^2; 1.80×10^3 dynes

d. 2×10^3 gms

Paragraph 22

a. 10^8 ergs

10^8 ergs

b. 5×10^{13} watts

Paragraph 29

1.95×10^5 cm/sec

Paragraph 35

a. 1.6×10^{-6} ergs

b. 2.3×10^{-3} dynes

2.3×10^{-11} ergs

c. 2.3×10^{5} dynes

2.3×10^{-7} ergs

Paragraph 43

a. 100 cps

b. 2×10^{4} cm

2 cm

c. 9.9×10^{-17} ergs

3.3×10^{-12} ergs

d. 2×10^{-5} cm

Ultraviolet

e. 2.42×10^{14} cps

1.24×10^{-4} cm

Infrared

f. 1.98×10^{-6} ergs

3×10^{20} cps

Gamma

Paragraph 61

a. 1.34×10^{23}

b. 1.20×10^{24}

Paragraph 61 (cont'd)

6.0×10^{23}

1.67×10^{-24} gm

6.0×10^{23}

3.33×10^{-24} gm

c. 1.49×10^{4} gms

Paragraph 69

a. 376 gm

1.085×10^{24}

9.00×10^{25}

b. 6.02×10^{22}

7.82 x 23

c. 6.60×10^{-5} cm

Visible

Paragraph 77

a. Isotope	Isobar
${}_{50}Sn^{124}$	${}_{52}Te^{124}$
${}_{50}Sn^{122}$	${}_{52}Te^{122}$
${}_{50}Sn^{120}$	${}_{52}Te^{120}$
${}_{50}Sn^{116}$	${}_{48}Cd^{116}$
${}_{50}Sn^{114}$	${}_{48}Cd^{114}$
${}_{50}Sn^{112}$	${}_{48}Cd^{112}$
${}_{50}Sn^{119}$	

Paragraph 77 (cont'd)

$_{50}Sn^{118}$

$_{50}Sn^{117}$

$_{50}Sn^{115}$

Paragraph 92

a. (1) 92 Mev

(2) 1614 Mev

(3) 1781 Mev

b. (1) 7.66 Mev/nucleon

(2) 7.80 Mev/nucleon

(3) 7.59 Mev/nucleon

Paragraph 105

a. β^-

b. 13.5 curies

518 days

c. (1) 1.382×10^{-11} sec

(2) 0.006 grams

d. (1) $_{92}U^{236}$

(2) $_{86}Rn^{220}$

Paragraph 123

a. (1) $_9F^{18}$

(2) $_8O^{17}$

b. 5.74 Mev

Paragraph 123 (cont'd)

c. 0.493 Mev

d. 0.1 barn

e. 206 cm

Paragraph 130

a. 600 barns

b. 44.8 barns

Paragraph 140

206 Mev

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